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TABLE OF CONTENTS

Isro Saputra, Menanga Puteri Hatami , Andria Maharani

57-70

Transit-Oriented Development in Emerging Cities: A Case Study of Railway Station Areas in Bandung, Indonesia
DOI: https://doi.org/10.51557/zer8bm80

Alvalo Toto Wibowo, Mochammad Karim Al Amin, Mohammad Thoriq Wahyudi, Hendri Budi Kurniyanto, Moh. Syaiful Amri, Moch. Aria Firmansyah, Rikky Leonard, Alvido Toto Wijaya

106-115

Analysis of Variation in the Number of Layers in the Hardfacing Process of ASTM A216 WCB Material on Hardness, Wear, and Microstructure
DOI: https://doi.org/10.51557/yknegr07

Fayza Maulidina, Farida Djumiati Sitania, Wahyuda Wahyuda

71-80

Distribution Truck Route Optimisation at UDMB Using The Clarke and Wright Savings and Cluster First Route Second
DOI: https://doi.org/10.51557/mv15pp96

Latifa Ummarah, Defi Irwansyah , Bakhtiar Bakhtiar

81-91

Analysis of Workplace Accident Risk Using The Hazard Identification Risk Assessment and Determining Control (HIRADC) Method in PMKS Pt. Sisirau
DOI: https://doi.org/10.51557/hcyphv13

Dicky Candra Ardiansyah, Tamara Latifah Jasmine, Hikmah Sekarningtyas

92-105

Selection of Primary Land Transportation Fleet Using Vehicle Operational Cost (VOC) Method in Logistics Companies
DOI: https://doi.org/10.51557/sqmhpw38

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Transit-Oriented Development in Emerging Cities: A Case Study of Railway Station Areas in Bandung, Indonesia

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Transit-Oriented Development (TOD); railway station; mobility; sustainable

Abstract

Transit-Oriented Development (TOD) is an urban concept that reduces dependence on private vehicles and promotes sustainable mobility. As one of Indonesia's metropolitan cities with a railway serving Bandung and its surrounding areas, Bandung can potentially adopt the TOD concept to address transportation and spatial planning issues. Therefore, this study takes three urban railway station areas as research objects, conducts a detailed evaluation of the comprehensive benefits of land use around these stations, and provides relevant recommendations. This study classifies urban railway transportation stations based on land use functions and establishes a three-tier comprehensive benefit evaluation index system across four dimensions: land use, population and building density, public transportation, and design. The research findings indicate that the Cikudapateuh stations meet five (5) basic TOD criteria, such as adequate pedestrian lane, mixed-use development, operational public transport service, public transport integration, and building coverage ratio (BCR). These findings indicate that TOD-based development in Cikudapateuh should be prioritized over the other two stations because it better meets the TOD criteria. The policy implications of this study recommend the need for synergy between spatial planning, strengthening transit infrastructure, and stakeholder participation to optimize TOD implementation, thereby achieving sustainable mobility in the future.

1. INTRODUCTION

Bandung is one of the largest metropolitan cities in Indonesia, serving as a hub for economic, educational, and tourism activities for both the people of Bandung and those in the surrounding areas. This has led to high mobility among the population, resulting in increasingly severe traffic congestion in Bandung year after year. According to research by Harahap et al. (2022), there are 8,565 vehicles per hour on the busiest roads, while the capacity of these roads is only 5,675 vehicles per hour. This suggests that Bandung needs to explore alternative solutions to reduce urban mobility. Conventional approaches, such as restricting private cars, are deemed insufficiently effective as they only address the user side, while improvements to transportation services are also necessary. An integrated alternative solution to reduce mobility is Transit-Oriented Development (TOD), which has been successfully implemented in various cities worldwide to create compact, walkable areas connected to mass transportation (Calthorpe, 1993; Handayeni, 2012).

TOD is a development model that integrates land use and public transportation, with three main principles: density, diversity, and pedestrian-friendly design (Calthorpe, 1993). Since the introduction of this concept in the 1970s, transportation-oriented development (TOD) has experienced rapid growth in Asian cities, such as Hong Kong. Railway stations are built alongside residential-commercial tower clusters and government services to form a new lifestyle – a "railway village." This concept has proven effective in reducing traffic congestion and air pollution and promoting economic growth, as seen in the successful implementation of TOD in Surabaya, which increased public transportation usage (Isa & Handayeni, 2014). Extensive literature on the interaction between land use and transportation has demonstrated that various land use characteristics,

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including density, diversity, design, proximity to public transportation, and destination accessibility, synergistically influence travel behavior. TOD (Transit-Oriented Development) is an example of integrating these characteristics, encouraging a shift from reliance on private vehicles toward public transportation and non-motorized modes of transport (Choi & Guhathakurta, 2024).

Although it has potential, implementing TOD in Bandung presents some challenges. A study by Widyahari & Indradjati (2015) found that the main obstacles are a lack of coordination between stakeholders and unclear criteria for land readiness. Additionally, transportation policy in Bandung metropolitan area continues to focus on building new roads rather than integrating various modes of transportation (Widyahari & Indradjati, 2015). However, stations such as Kiaracondong, Cikudapateuh, and Bandung have high accessibility and are surrounded by commercial areas and residential neighborhoods, thereby meeting the basic principles of TOD. This study aims to identify the suitability of TOD principles in the Bandung Station Area, Kiaracondong Station, and Cikudapateuh Station based on land use, accessibility, and pedestrian infrastructure. Additionally, this study will provide policy recommendations to accelerate the implementation of TOD in Bandung.

2. LITERATURE REVIEW

Transit-Oriented Development (TOD) is an urban planning approach that aims to integrate mass transportation systems—particularly railways—with the development of surrounding areas in an integrated manner. This concept emerged in the 1970s as an innovative solution to address issues such as traffic congestion, inefficient land use, and environmental degradation resulting from reliance on private vehicles (Calthorpe, 2014; Cervero & Dai, 2014). According to Calthorpe (1993), TOD is a compact, transit-supportive, mixed-use development oriented toward pedestrians. The main principles of TOD, as formulated by Cervero & Kockelman (1997), are the "3Ds": Density, Diversity, and Design. These three factors are believed to reduce dependence on motor vehicles by improving accessibility through transit routes and facilitating sustainable mobility.

Furthermore, Cervero and Murakami (2009) expanded this principle into "5D," which includes: Density, Diversity, Design, Distance to transit, and Destination accessibility. Their research emphasizes that the success of TOD is not only influenced by physical factors but also by adequate distance and accessibility, thereby reducing travel time and increasing the area's attractiveness. Another study by Song & Knaap (2004) states that the success of TOD depends on strong integration between spatial planning, transportation, and economic development. Song & Knaap (2004) emphasize that fiscal policies and incentives are crucial in encouraging developers to build in TOD zones, especially in areas with primary access to train stations. There is also research on the optimal distance from a train station for development (Huang et al, 2021). Typically, a distance of approximately 400-800 meters from the station is ideal for pedestrians and public transportation users, equivalent to a walking time of about 5-10 minutes (Jiao et al, 2014; Calthorpe, 1993; Porter, 1997). In this area, development with a density and diversity of land use is most effective in increasing transit use and reducing the use of private vehicles.

Hong Kong is one example of the successful implementation of TOD in the form of "rail villages," which are areas that have developed around railway stations designed as centers of economic and social activity (Xue & Sun, 2018). Most stations in Hong Kong are surrounded by clusters of residential and commercial developments, indicating that the success of this development is supported by government policies that promote the integration of urban planning and transportation. In this study, Xue and Sun (2018) introduce the concept of development ratio to measure the efficiency of development around stations, reflecting the direct relationship between the level of development and the success of such development. The research findings suggest that dense and mixed-use development enhances accessibility, optimizes land use, and reduces the need for long-distance travel. In addition to Hong Kong, other countries such as Japan, South Korea, and Singapore have also extensively implemented the TOD concept. Studies by Kamruzzaman et al. (2014) in Brisbane, Australia, and Kikutake et al. (1960) on urban metabolism indicate that the success of TOD across

different cultures and contexts must adapt to local conditions, including walking culture, development regulations, and economic incentives.

The main benefits of TOD include increased use of public transportation, reduced traffic congestion, improved environmental sustainability, and increased property values around stations (Ewing & Cervero, 2010; Song & Knaap, 2004). Additionally, TOD can create a more pedestrian-friendly environment, improve quality of life, and strengthen the local economy. However, key challenges include regulatory constraints, high development costs, resistance from developers and residents, and the need for comprehensive long-term planning (Knaap et al., 2001). In Hong Kong, strict land use regulations and topographical conditions hinder large-scale development.

Table 1 Synthesis of Transit-Oriented Development (TOD) Literature

Variable	Renne	ITDP (2017)	LVPC (2011)	Regulation of the Minister of Land and Spatial Planning No. 16/ 2017	Synthesized Criteria
Land Use Diversity	- Multi-family homes - Office/retail dominant along main roads	- Mixed uses to reduce travel distance	NA	**Urban centre**: - 20–60% residential, 40–80% non-residential - ≥5 land uses (housing, commercial, office, culture, public facilities) - High/mid-rise housing - 10–15% open space (+20% public green **Sub-urban centre**: - 30–60% residential, 40–70% non-residential - ≥4 land uses - 10–15% open space (+20% public green space)	**Urban centre**: - ≥5 land uses; - 20–60% residential - 40-80% non-residential - 10–15% open space (+20% public green space) **Sub-urban centre**: - ≥4 land uses; 30–60% residential - Office: 30–70% - Public space: 5–15% - 10–15% open space (+20% public green space)
Density	- High density	- High-density housing/jobs near transit	**Housing**: - Urban centre: >20 people/ha - Sub urban: >35 people/ha **Jobs:** - >50 peopla/ha	**Population**: - Urban centre: >750/ha - Sub-urban centre: 450–1500/ha **Jobs**: - Urban centre: >200/ha - Sub-urban centre: 40–200/ha **Housing**: - Urban centre: 20–75 units/1000 m² - Sub-urban centre: 12–38 units/1000 m²	**Population:** >750 people/ha **Housing:** - Urban centre: 20–75 units/1000 m² - Sub-urban centre: 12–38 units/1000 m²
Design (Accessibility)	- Grid street patterns - Pedestrian-focused	- Safe bike/pedestrian networks - Walkable transit access	NA	- 400–800m radius (physical boundaries) - Grid streets - Sidewalks on all roads	- Bike lane - Adequate pedestrian lane
Intensity (Building Floor Area Ratio and Building Coverage Ratio)	- Compact development	NA	NA	**Urban centre**: - BFAR >5.0 - High-rise (11–40 floors) - BCR 80% max lot coverage **Sub-urban centre**: - BFAR 3.0–5.0 - Mid-rise (3–15 floors) - BCR 70% max lot coverage	**Urban centre**: - BFAR >5.0 - BCR 80% max lot coverage **Sub-urban centre**: - BFAR 3.0–5.0 - BCR 70% max lot coverage

Variable	Renne	ITDP (2017)	LVPC (2011)	Regulation of the Minister of Land and Spatial Planning No. 16/ 2017	Synthesized Criteria
Public transport service	NA	NA	- Headway <15 min - 17h/day service - Commuter train 20 times a day	**Urban centre**: - Headway <5 min - Multi-modal (BRT, minibuses, and rail) **Sub-urban centre**: - Headway 5–15 min - Multi-modal (BRT, minibuses, and rail)	- Headway ≤15 min - 17h/day service - Commuter train 20 times a day - There are public transportation routes

Theoretically, literature indicates that the success of TOD is greatly influenced by density regulations, land use diversity, pedestrian-friendly infrastructure design, and optimal distances from train stations. Successful implementation has proven capable of creating more sustainable urban environments and a better quality of life. In the future, the need for supportive policies, economic incentives, and community participation will be crucial in driving the widespread development of TOD.

3. METHODS

This study employs a mixed-methods approach, integrating quantitative descriptive analysis and qualitative comparative evaluation to assess the potential for Transit-Oriented Development (TOD) implementation at Kiaracondong Station, Bandung Station, and Cikudapateuh Station. The methodology is structured into three phases: (1) data collection, (2) multi-criteria analysis, and (3) comparative benchmarking against global TOD standards. This approach ensures a comprehensive evaluation of land-use diversity, transport accessibility, and urban density, aligning with established TOD frameworks (Cervero & Kockelman, 1997; ITDP, 2017).

Primary and secondary data were collected to ensure analytical rigor. Secondary data included regulatory reviews of Indonesia's TOD guidelines, the Minister of Land and Spatial Planning Regulation No. 16/2017, and global best practices from the Institute for Transportation and Development Policy (Ministry of Land and Spatial Planning, 2017; ITDP, 2017). Geospatial and demographic datasets were sourced from government agencies. The primary data consisted of field surveys conducted at selected transit nodes, measuring pedestrian infrastructure, public transport service quality, and land-use mix.

Next, a qualitative approach is employed, utilizing a comparative analysis method. This method aims to identify gaps between actual conditions and TOD principles through systematic comparison (Nazir, 2005). Variables like land use, parking availability, and transportation mode integration were compared with global TOD criteria. The quantitative approach is used to assign a score to each variable. A score of 1 is assigned to variables that meet TOD principles, and a score of 0 is assigned to those variables that do not meet the principles. The scores will be calculated as the percentage of compliance for each variable (Giffary et al., 2022). The results are visualized in a suitability matrix to determine the area's readiness level.

The Land Use Mix Index is also calculated in this study by comparing the area of residential and non-residential land (Burton, 2000). To analyze land use mix, it is essential to define a spatial radius to accurately interpret the TOD area. In this study, the spatial radius is 600 metres, which was clipped by the ArcGIS software (Calthorpe, 1993). An index value close to 1 indicates an ideal balance for TOD, while a value greater than 1 indicates a dominance of residential areas that require functional diversification intervention. The following formula is used to calculate the land use mix index.

$$\textbf{\textit{Land use mix index}} = \frac{(\textbf{\textit{Residential land area}})}{\textbf{\textit{District area}} - \textbf{\textit{Residential land area}}}$$

Next, density analysis was measured using a composite index that combines population density, settlement density, and built-up land density. Areas with index values above the 75th percentile are considered to meet

TOD density requirements, while values below the 25th percentile require density increase policies. Measuring the intensity of building utilization is also conducted in this study, where building intensity is the allocation and distribution of the maximum floor area of a building relative to its designated land/site to achieve good efficiency and effectiveness of utilization. Building utilization intensity consists of the Building Floor Area Ratio (BFAR) and Building Coverage Ratio (BCR), calculated using the following formula (Regulation of the Minister of Public Works No. 06/2007).

$$\boldsymbol{BFAR = Number\ of\ Floors \times Land\ area}$$

$$\boldsymbol{BCR = \frac{Building\ area}{Land\ area} \times 100\%}$$

Finally, public transportation services can be analyzed based on the modes of public transportation that serve the station area and their frequency of service. The modes of public transportation that serve the station are intended to determine whether the train station is integrated with other modes of public transportation, such as Minibuses and BRT. Minibuses and BRT are also evaluated based on the daily number of vehicles per route operating in the planned area. In addition to minibuses and BRT, the frequency of commuter trains served at each station is also assessed, including headway, type of train service, number of train units, and daily train operations.

4. RESULTS

This section will present the analysis results based on the previously determined methods. The results section comprises six subsections: mixed land use, density analysis, public transport services, design (accessibility), building intensity analysis, and a comparative analysis of the three stations.

4.1 Land use diversity

A land use diversity analysis was conducted using the buffer method in ArcGIS software to determine the radius of the area. Based on Regulation of the Minister of Land and Spatial Planning No. 16/2017, the radius was determined to be 600 meters from the transit point. Other provisions state that an area that can be developed into a TOD must have at least five land use types, consisting of 20-60% residential and 40-80% non-residential, including 30-70% office centers and 5-15% open spaces. The Land Use Mix Index calculation was also used in the analysis to assess the potential for TOD development.

Based on the analysis results, it was found that the three study areas—Bandung Station, Cikadapateuh Station, and Kiaracondong Station Area—have more than five land use types. The Bandung Station Area comprises 72.3% residential, 26.9% non-residential, 19.4% office center, and 0.8% open space. The land use mix index for the Bandung Station Area shows a value of 2.62. This means that, based on land use composition and land use mix index criteria, the Bandung Station Area does not yet meet the requirements for a TOD area.

The Cikudapateuh Station area comprises 72.5% residential, 20.7% non-residential, 12% office and commercial center, and 6.9% open space. Additionally, the mixed land use index calculation yields a value of 2.63. The Kiaracondong Station Area comprises 80.9% residential, 13.2% non-residential, 3% office and commercial center, and 5.9% open space. The land use mix index for this area reaches 4.24. Based on the analysis of land use diversity and the land use mix index, it can be concluded that the Cikudapateuh Station Area and Kiaracondong Station Area do not yet meet the criteria for TOD potential. Figure 1 below provides an overview of land use composition at the three study areas.

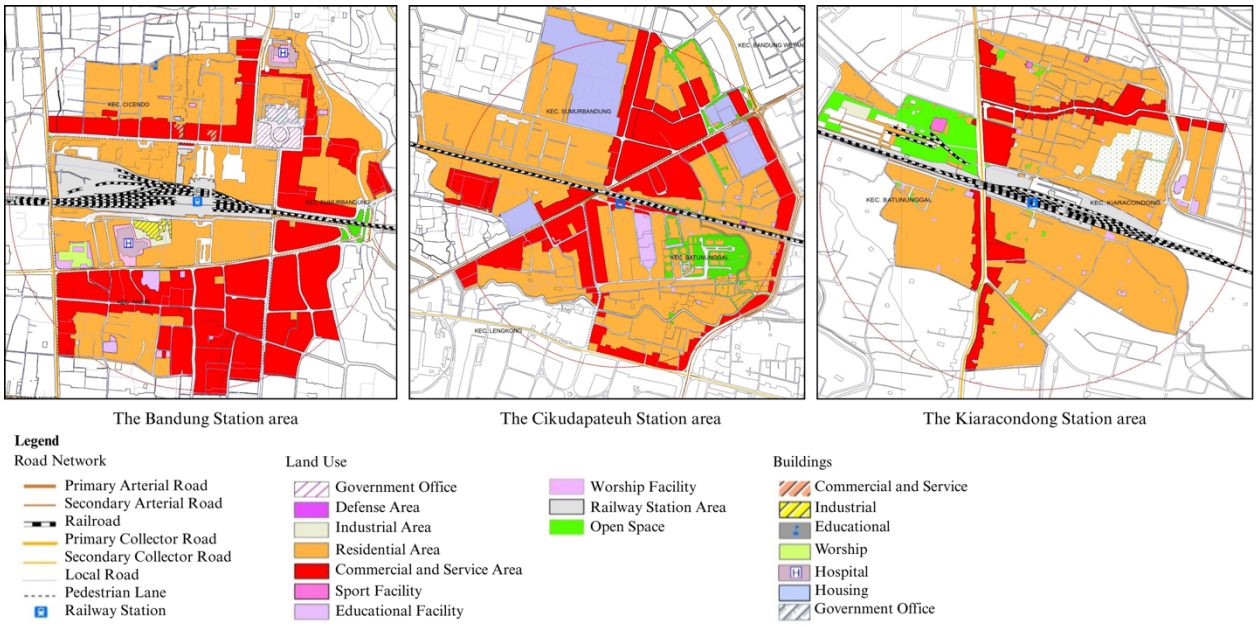

Figure 1. Map of landuse in the study areas

4.2 Density

Density analysis consists of population density and building density. To support the criteria for implementing TOD, an area was determined to have a high population and building density. Based on Regulation of the Minister of Land and Spatial Planning No. 16/2017, to fulfill the TOD criteria, the population density must be greater than 750 people/ha, and the housing density must be between 20 and 75 units/1000 square meters.

According to the analysis results, the Bandung Station area has a population density of 175 people/ha and a housing density of 4 units/1000 m2. The Cikudapateuh Station area has a population density of 320 people/ha and a housing density of 8 units/1000 m2. The Kiaracondong Station area has a population density of 420 people/ha and a housing density of 6 units per 1,000 square meters. This indicates that none of the three study areas meet the criteria for a TOD zone. Population and housing density remain low compared to the established criteria.

4.3 Design (Accessibility)

Accessibility analysis in TOD consists of bike lanes and pedestrian lanes. These elements facilitate convenience in reaching destinations by offering various alternative routes to the destination location. This study includes observations regarding the condition of the bike lane and the pedestrian lane at each study area.

The Bandung Station area is dominated by residential, commercial, and service areas, drawing significant pedestrian traffic. To facilitate pedestrian movement, the pedestrian lane features a width ranging from 2.5 to 4 meters. This width is generally considered suitable for pedestrian use; however, the condition is inadequate due to street parking and extensive tree roots protruding onto the path. Consequently, pedestrians often experience discomfort and walk on the roadway. Furthermore, the area lacks a designated bike lane, forcing cyclists to use the same space as motorized vehicles.

Figure 2. Pedestrian Lane on Bandung Station Area

The Cikudapateuh Station area has various land uses which dominated by residential and commercial and service area. The features of pedestrian lane exceeds 2 meters. Generally pedestrian lane in this area adequately provided along the main thoroughfare, Jl. Ahmad Yani, yet neighborhood areas in the vicinity lack sufficient pedestrian lane. These areas are narrower, measuring less than 2 meters, and are often obstructed by tree roots. The comfortable pedestrian lane primaly is only to Ahmad Yani Street and Malabar Street. Furthermore, the Cikudapateuh Station area lacks designated bike lane, forcing cyclists to use the same space as motorized vehicles.

Figure 3. Pedestrian Lane on Cikudapateuh Station Area

The Kiaracondong Station is dominate by residential and commercial and service are. The average width of pedestrian lane exceeds 2 meters. However, their condition is compromise by the presence of street vendors. The existence of Kiaracondong market significantly contributes to the deterioration of the traffic, as many traders operate outside the market. The pedestrian lane is available along Ibrahim Adjie Street, which are often in poor condition, obstructed by waste and big trees. Furthermore, the Kiaracondong Station area lacks designated bike lane, forcing cyclists to use the same space as motorized vehicles.

Figure 4. Pedestrian Lane on Kiaracondong Station Area

4.4 Intensity

The analysis of space intensity in this study includes the existing building floor area ratio (BFAR) and building coverage ratio (BCR) values. This analysis is used to compare the existing ratios with the ratios specified in Regulation of the Minister of Land and Spatial Planning No. 16/ 2017. The BFAR criteria that must be met for the central city area are >5.0 and 3.0-5.0 for the suburban center. Meanwhile, the BCR criteria are 80% for the central city area and 70% for the suburban center.

Based on the results of the analysis, it was found that the Bandung Station Area has an average BFAR of 1.70 and a BCR of 47% of the required 80%. This means the BFAR criteria are not yet met as a TOD potential because no buildings with a mixed-use concept exist in this area. The buildings have their respective functions and are not integrated. However, the BCR value still meets the criteria for land coverage. The Cikudapateuh Station Area has an average BFAR of 1.39 and a BCR of 57% of the required 70%. The Kiaracondong Station area has an average BFAR of 0.91 and a BCR of 52% of the required 70%. Both areas show low BFAR values, thus failing to meet the criteria for TOD potential. This is due to the absence of buildings with a mixed-use concept in these areas. Meanwhile, the BCR value still meets the requirements as it is below the maximum value.

4.5 Public transport service

Based on Appendix II of Regulation of the Minister of Land and Spatial Planning No. 16/2017, it is explained that a key prerequisite for the development of TOD areas is the development of a public transportation system, as it can create a market as an attraction for activities around transit hubs. The success of TOD is influenced by the number of public transport users at transit hubs. It indicates that the presence of stations is a urgently for supporting TOD areas. Public transportation analysis refers to the modes of public transportation operating around the station, as well as their service frequency. The modes of public transportation referred to in this study are intended to examine the integration of other modes with the train station, including minibuses and buses. The indicators examined for these public transportation modes include the number of vehicles per route passing through the study area each day. Additionally, the frequency of commuter trains served at each station is analyzed, including headway ≤15 minutes, type of train service, 20 times a day for commuter trains, and train operations for 17 h/day service.

Public transportation services around Bandung Station are known to include 17 (seventeen) minibus routes and 2 (two) bus (BRT) routes that pass through the area. In this regard, Bandung Station is well-integrated with other public transportation modes, providing convenient accessibility for train passengers to the surrounding areas without the need for private vehicles. The high number of routes results in many vehicles passing through the area, reaching up to 130 units per day. In serving commuter trains, Bandung Station operates for 20 hours, serving three main destinations: the Bandung Raya Local Train to Cicalengka, which has 18 train sets with a headway of 55 minutes; the commuter train to Padalarang, which has 19 train sets with

a headway of 1 hour; and the Bandung Raya Train to Cibatu and Purwakarta, each of which has only one train set and operates at one time only.

Next, public transportation services around Kiaracondong Station have only 8 (eight) minibus routes. In serving commuter trains, this station serves local and commuter trains for three main destinations. The services that operate consist of the Bandung Raya Local Train, which has routes from Padalarang to Purwakarta and Cicalengka to Cibatu; the Cibatu/Simandra Local Train, with destinations to Purwakarta and Cibatu; and the Galunggung Train, which has a destination to Tasikmalaya. Each destination has different operating hours: 20 hours for the Bandung Raya Local Train to Cicalengka, Padalarang, and Cibatu, while the local train to Cibatu only operates for 2 hours. 8 (eight) minibus routes serve access to the area around Kiaracondong Station, and no bus routes pass through this area. This is due to the narrow roads around the market leading to Kiaracondong Station, which is caused by the expansion of street vendors onto the roadways.

Finally, Cikudapateuh Station is smaller than Bandung and Kiaracondong Stations. Public transportation services around this area include 3 (three) minibus routes and 3 (three) bus routes. This station serves only the commuter trains, AC Patas KRD, and Bandung Raya Patas KRD routes to Cibatu and Bandung Raya. This station operates for 17 hours, serving passengers for routes to Padalarang, Cicalengka, Purwakarta, and Cibatu. Looking at the public transportation routes passing through the station, there are 3 (three) minibus routes and 3 (three) bus routes. Despite having limited routes, the station's location is strategically positioned to access shopping centers such as the Kosambi market.

4.6 Comparison of three stations

A comparative analysis was conducted to compare the characteristics of the three study areas and determine which one has the potential to apply the TOD concept. Based on the analysis results, it can be concluded that the three study areas have potential for implementing the TOD concept. The Cikudapateuh Station Area has greater potential as its existing conditions are suitable for the criteria of TOD as it has higher scoring than other areas namely 35%. This analysis indicates that each station shares similar characteristics. However, their respective analyses yield differing suitability values. The following are the results of the comparison:

Table 2. Results of the comparative analysis of TOD criteria at three stations

No	Variable	Criteria	Results			Score		
			A	B	C	A	B	C
1	Land Use Diversity	**Urban centre**: - ≥5 land uses; - 20–60% residential - 40-80% non-residential - 10–15% open space (+20% public green space)	≥5 land uses 72.3% residential 26.9% non residential 0.8% open space	≥5 land uses 72.5% residential 20.7% non residential 6.9% open space	≥5 land uses 80.9% residential 13.2% non residential 5.9% open space	1 0 0 0	1 0 0 0	1 0 0 0
2	Density	**Population:** >750 people/ha **Housing:** 20–75 units/1000 m²	175 people/ha 4 units/ 1000 m²	320 people/ha 8 units/ 1000 m²	420 people/ha 6 units/ 1000 m²	0 0	0 0	0 0
3	Design (Accessibility)	- Bike lane - Adequate pedestrian lane	- No bike lane - Inadequate pedestrian lane	- No bike lane - Adequate pedestrian lane	- No bike lane - Inadequate pedestrian lane	0 0	0 1	0 0
4	Intensity (Building Floor Area Ratio and Building Coverage Ratio)	**Urban centre**: - BFAR >5.0 - BCR 80% max lot coverage	BFAR 1.70 BCR 47%	BFAR 1.39 BCR 57%	BFAR 0.91 BCR 52%	0 1	0 1	0 1

No	Variable	Criteria	Results			Score		
			A	B	C	A	B	C
5	Public Transport Service	- Headway ≤15 min - 17h/day service - Commuter train 20 times a day - There are public transportation routes	- Headway 55 min - 20h/day service - Commuter train 18 times a day - 17 routes of minibus and 2 routes bus (BRT)	- Headway 60 min - 17h/day service - Commuter train 18 times a day - 3 routes of minibus and 3 routes bus (BRT)	- Headway 58 min - 20h/day service - Commuter train 17 times a day - 8 routes of minibus (BRT) (√)	0 1 0 1	0 1 0 1	0 1 0 1
					Total	29%	35%	29%

A= Bandung Station
B= Cikudapateuh Station
C= Kiaracondong Station

Scoring:
(1) fulfills Transit Oriented Development TOD criteria
(0) does not fulfill Transit Oriented Development TOD criteria

5. DISCUSSION

This study identifies the application of the Transit-Oriented Development (TOD) concept in Bandung, focusing on three railway stations: Bandung Station, Cikudapateuh Station, and Kiaracondong Station. The analysis results indicate that all three stations share similar aspects that meet the TOD criteria, with Bandung Station and Kiaracondong Station meeting 4 out of 14 TOD criteria, and the other station meeting 5 out of 14 criteria. This indicates that Cikudapateuh Station is the most suitable for implementing the TOD concept. At the same time, the other stations also have potential but still need to meet many of the main criteria. This finding addresses the recommendations from the research by Widyahari & Indradjati (2015), which stated that these three stations are potential and require further study. However, the results of this study differed, as implementing TOD at the three stations still requires meeting approximately 9–10 TOD criteria.

A key finding of this study is the imbalance in land use proportions at the three stations, where residential areas account for more than 70% of the area. This contradicts the TOD principle, which emphasizes a balance between residential (20-60%) and non-residential (40-80%) areas (Ministry of Land and Spatial Planning, 2017). A similar condition was also found in Isa & Hadayeni (2014) study in Surabaya, where the dominance of residential areas hindered the development of TOD areas by reducing space for commercial and public activities. At Bandung Station, for example, the low proportion of open space (0.8%) and office centers (19.4%) became the main obstacles, necessitating policy interventions to regulate a more balanced land allocation. This means that at all three stations, only the criteria for five types of land use were filled, while the portion of land use wasn't filled. This situation may be caused by minimal control over land use and the lack of incentive mechanisms for developing mixed-use buildings in the station area.

Although Isa & Hadayeni's (2014) research revealed that the implementation of TOD in Surabaya was quite successful, the criteria for land use proportion were not met, which explains that residential land dominates TOD areas. In line with our findings, the failure to meet the land use proportion criteria in all three TOD areas indicates that the dominance of residential functions in Transit-Oriented Development (TOD) areas is a common phenomenon in Indonesia. This finding challenges the assumption of the universality of Cervero's (1998) TOD model by showing that density does not automatically create diversity without strong policy intervention. Therefore, measures such as form-based zoning, progressive tax incentives, and land value capture mechanisms are needed to achieve sustainable and balanced TOD. Moreover, the Detailed Spatial Planning and Zoning Regulations of Bandung City for the period 2015-2035 stipulates that the three designated study areas are classified as high-density residential zones. This further indicates that the high density of residential areas occurs systematically, but on the other hand it can hinder the implementation of the TOD concept.

Bandung Station has the best public transportation integration with 17 minibus routes and two bus routes, while Kiaracondong Station is only served by minibuses. However, the frequency of train services in all three areas is currently low (headway of 1 hour), which does not meet the TOD standard (<15 minutes). These findings are consistent with Isa's (2014) research, which highlights the need to improve the frequency and quality of public transportation services to support TOD. Additionally, the lack of pedestrian facilities and bike lanes in all three areas hinders the creation of a walkable and bikeable environment, as explained in Renne's (2009) study.

Density analysis reveals that Kiaracondong Station has the highest population density (420 people/ha), yet it remains below the TOD standard for urban centers (exceeding 750 people/ha). Meanwhile, Bandung Station only reaches 175 people/ha, which is far from the ideal criteria. This low density is related to the dominance of inefficient horizontal settlements. In addition, building density is also very low in all three locations, with Bandung station having 4 units/1000 m², Cikudapateh 8 units/1000 m², and Kiaracondong station 6 units/1000 m². Research by Pushkarev and Zupan (1977) suggests that to support sustainable transportation, a high building density is necessary for an area, making vertical housing development and increased building intensity recommended solutions.

Aspects of area design, such as the availability of sidewalks and bicycle lanes, were also highlighted in this study. Although the sidewalks at all three stations met the minimum width standard (2 meters), many were in poor physical condition due to street activities and illegal parking. This reduced the comfort of pedestrians and people with disabilities, who should be a priority in TOD development (ITDP, 2017). A study by Handayeni (2012) also found that the inconvenience of pedestrian facilities is the main obstacle to implementing TOD. Therefore, improving sidewalks and adding bike lanes should be a focus in development plans.

Based on the analysis, the study findings reveal conflicts between theory and actual conditions, such as pedestrian lanes that are physically adequate but uncomfortable due to conflicts with informal activities (Cervero & Kockelman, 1997), or the availability of diverse modes of transportation with low frequency, rendering them ineffective (ITDP, 2017). This paradox suggests that physical indicators in TOD planning are insufficient on their own and must be examined holistically within the socio-economic context of the area. For example, the presence of poorly maintained pedestrian facilities reflects weak spatial management coordination, while low public transport frequency is linked to institutional fragmentation (Ray et al., 2020). This reflection highlights that the success of TOD depends not only on design but also on the integration of policies that are responsive to societal dynamics.

This study makes both theoretical and empirical contributions to the field of Transit-Oriented Development (TOD) in an emerging city. Theoretically, it refines the understanding of TOD principles within the Indonesian context by highlighting the common phenomenon of residential dominance in TOD areas and challenging the universal applicability of existing TOD models. This calls for a more nuanced approach that considers local conditions and strong policy interventions to achieve balanced land use. Empirically, the study provides a comparative assessment of three railway station areas in Bandung, identifying Cikudapateuh Station as the most suitable for TOD implementation. It identifies specific areas for improvement at all three stations, including increasing the frequency of train services, developing mixed-use vertical housing, and enhancing pedestrian facilities. These findings offer practical insights for policymakers and urban planners in Bandung and other similar cities seeking to implement TOD strategies. The research highlights the importance of collaboration among the government, the private sector, and the community in achieving sustainable and inclusive urban development.

Overall, this study confirms previous findings that the implementation of TOD depends on the availability of transportation infrastructure and the balance of land use, density, and pedestrian-oriented area design. Recommendations for TOD development in Bandung include: (1) increasing the frequency of train services, (2) developing mixed-use vertical housing, (3) improving pedestrian facilities & bike lanes, and (4) balancing land allocation for residential and non-residential areas. Implementing these policies requires collaboration

between the government, private sector, and community, as explained in Widyahari & Indradjati (2015) study on TOD development in the Greater Bandung Metropolitan Area.

6. CONCLUSIONS

This study identifies that the concept of Transit-Oriented Development (TOD) can be applied in Bandung, particularly in the Cikudapateuh Station area, as it meets several key criteria, such as land use diversity, building coverage ratio (BCR), adequate pedestrian lanes, and public transportation integration. However, the high dominance of residential land use and the imbalance between residential areas and non-residential facilities indicate the need for a more holistic approach in TOD planning. TOD theory emphasizes the balance of residential, commercial, and public spaces to create sustainable areas that are integrated with mass transportation. The results of this study confirm the hypothesis that the success of TOD depends not only on the availability of transit modes but also on comprehensive spatial planning, including density regulations, mixed-use development, and accessibility for pedestrians and bikes.

Based on the study's findings, the Bandung City Government needs to develop policies that encourage the implementation of TOD through revisions to zoning regulations to ensure a balanced land use ratio, particularly by increasing the proportion of commercial and public spaces around stations. Additionally, collaboration is needed among relevant agencies, such as the Transportation Department and the Spatial Planning Department, to enhance public transportation integration and provide adequate pedestrian infrastructure and bicycle lanes. Incentive policies for developers to build vertical housing and mixed-use buildings can also be a solution to optimize land use. These steps will support the creation of TOD areas that reduce dependence on private vehicles and improve the community's quality of life through a sustainable and inclusive environment. Additionally, we recommend implementing vertical residential areas in the TOD 3 station area to balance the proportion of each land use, considering that residential areas are currently the dominant land use. This approach can improve spatial efficiency while supporting the principles of TOD.

The limitations of this study lie in its scope, which focuses only on existing railway stations in Bandung City, without considering other transit points such as bus terminals or city transport stops, and does not include future public transport development plans such as LRT. Additionally, this study has not examined population density based on occupation type, which could provide a more in-depth understanding of transportation needs. Furthermore, the study has not explained the quality of physical indicators, such as criteria for pedestrian accessibility from both social and economic perspectives. For future research, it is recommended to expand the scope of the analysis to include various types of transit points, integrate plans for new transportation modes, and conduct a more detailed classification of population density based on economic activities, and delve deeper into the social and economic aspects of each physical indicator to enhance the accuracy and relevance of the research findings.

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Distribution Truck Route Optimisation at UDMB Using The Clarke and Wright Savings and Cluster First Route Second

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Clarke and Wright Savings; Cluster First Route Second; Nearest Neighbor; Sweep Algorithm; Transportation

Abstract

UDMB is a distributor company of frozen food products in East Kalimantan and North Kalimantan. Time and distance are the biggest obstacles felt by companies in the distribution process. It is because the product must be at a minimum temperature of -18o Celsius so that the product remains in good condition. Meanwhile, the cooling machine on a distribution truck can only maximize working temperature for 6 hours. These travel time and distance problems have occurred more than 12 times a year in out-of-town distribution. Therefore, this research aims to produce an optimal distribution routes with consideration of the fastest time and shortest distance. This problem is solved using the Clarke and Wright Savings Method with the Head and Tail concept and the Cluster First Route Second Method with Sweep Algorithm and Nearest Neighbor. Then, the total distribution time and distance between the results of the two methods are compared. Based on the first results, the total trucks used are 3 units with a total distribution time of 847 minutes and a total distribution distance of 475.8 km. Based on the second results, the total trucks used are 3 units with a total distribution time of 875 minutes and a total distribution distance of 483.8 km. This shows that the Clarke and Wright Savings Method with the Head and Tail concept is the method that produces the most optimal route with the fastest total distribution time and shortest total distribution distance.

1. INTRODUCTION

Problems related to distribution are the biggest obstacle for companies, especially in Supply Chain Management because they are dealing with partners that can affect the sustainability of the supply chain (Saragih, 2024). Distribution is defined as an activity that includes planning, implementing and monitoring the flow of materials to obtain the final product from the place of production by obtaining profits using transportation. Usually, transport problems can be in the form of varying amounts of goods transported which will result in different profits and costs so that the solution to the problem is to determine the number of units of goods that must be transported (Sekarningtyas et al., 2023). That way, the distribution and transport network needs to be done optimally because it is one of the important factors that affect the amount of expenses and income in a company. One of the steps that can be taken to make the process more efficient is to make proper distribution and transportation planning so that products can reach customers on time (Wulandari and Mulyanto, 2024).

Optimal route planning can be done when the organisation experiences a problem that arises in the distribution and transportation department. These problems are generally related to the value of place and time obtained based on the varied products distributed. These values can be analysed to find solutions to the causes and effects. Thus, the company managing the distribution system can take the necessary actions to optimise the use of its transportation resources.

Distribution and transport route planning can be solved using the Vehicle Routing Problem (VRP). The Vehicle Routing Problem (VRP) was first introduced by Dantzig and Ramser in 1959 and is a development of the Traveling Salesman Problem. In the VRP problem there is more than one vehicle that visits each customer

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and the customer can only be visited once (Widyastiti and Sumarsa, 2023). There are four general objectives in the Vehicle Routing Problem (VRP), namely minimising transportation costs related to distance and fixed costs associated with vehicles, minimising the number of vehicles (or drivers) needed to serve all consumers, balancing routes for travel time and vehicle load, and minimising complaints from consumers due to unsatisfactory service (Wulandari, 2020). There are several variations of the Vehicle Routing Problem (VRP), namely VRP with multiple trips, VRP with capacitated, VRP with time window, VRP with split deliveries, VRP with multiple products, Periodic VRP, VRP with multiple depots, VRP with heterogeneous fleet of vehicles, Stochastic VRP, and Dynamic VRP (Pertiwi et al., 2020). The types of VRP in this research are VRP with capacitated, VRP with time window, and VRP with multiple products.

The examples of research using these methods are research by Setiawan and Suseno (2024) using the Clarke And Wright Savings and Sequential Insertion Methods, Afriana et al. (2023) using the Clarke And Wright Savings and Nearest Neighbor Methods, Yusuf and Sukoyo (2023) using the Clarke And Wright Savings Method, Solihin et al. (2023) using the Cluster First Route Second Method, and research by Putri et al. (2021) using the Genetic Algorithm Method with Cluster First Route Second. Whereas in this study, the Vehicle Routing Problem (VRP) approach used is Clarke And Wright Savings developed using the Head and Tail concept, and Cluster First Route Second using Sweep Algorithms and Nearest Neighbor. This research compares the two types of Vehicle Routing Problem (VRP) approaches with methods that have been developed to see which approach has the most optimal results.

One of the companies that experience problems in the distribution and transportation section is UDMB. UDMB is the main distributor of frozen food products in East Kalimantan and North Kalimantan. The company distributes out of town and within the city based on incoming requests from the intended partners. Time and distance are the biggest obstacles felt by the company in the distribution process outside the city because the product must be at a minimum temperature of -18^{o} Celsius so that the product remains in good condition. Meanwhile, the cooling machine on the distribution truck can only maximise the temperature work for 6 hours and the temperature will start to drop as the distance and travel time increase to the last point. In addition, the company also needs to meet the minimum turnover value requirement of one hundred million rupiah in one out-of-town distribution trip. If the number in this requirement is not achieved, the company needs to add other partners as additional location points so that distribution can be carried out. Thus, the distribution system in this company is not included in the regular route type, which means that the company does not have a set route but the route depends on the changing demand conditions of each partner.

The problem of travelling time and distance has occurred more than 12 times a year. One of them occurs in 7 out-of-town partners. The company conducts the distribution process once a month with a six-wheeled truck. Each partner gets a supply of frozen food products in the form of processed meat distributed directly by the company. In the distribution process, the company always tries to maximise the volume of cargo, which is 9 m^3 to meet all requests to achieve the specified turnover value requirements. In fact, the company has an allowance volume that needs to be considered at 25% of the truck load volume. This is because frozen food products require good cold air circulation from the cooling machine on the truck box so that the product remains in good condition. This causes a decrease in truck performance, namely truck speed that becomes not optimal and causes the product to experience open vaccum seal damage so that the company experiences losses in the form of unsalable products. The distribution process is known to take approximately 9 hours with the destination of the farthest point (A7) which has exceeded the time limit of the cooling machine on the distribution truck.

Therefore, in an effort to minimise the losses caused by this problem, it is necessary to optimise the distribution truck routes. Route optimisation for distribution trucks to each point is carried out by taking into account the volume of cargo, the weight of the cargo, and the time to complete the distribution. The route results will consider the fastest time and shortest distance using the Clarke and Wright Savings Method with the Head and Tail concept and the Cluster First Route Second Method with Sweep Algorithms and Nearest

Neighbor. The results of this study are expected to help companies as input and evaluation material in achieving the desired goals.

2. METHODS

This research begins with a preliminary study to gather information of the company. Then, it continued with problem identification through observation and initial interviews in order to formulate and determine objectives. In solving the problem, data collection is carried out consisting of initial loading time data, unloading time for each stop, demand data, distance and time data between points, coordinate data for each point, product prices, truck capacity, truck box dimensions, and product box dimensions. The data collection was carried out by direct observation and interviews with the company. In addition, data related to distance and time was obtained using the help of google maps. The data is used to represent the real condition of the company into a mathematical model. Then, data processing is carried out using the data analysis techniques performed that can be described as follows.

2.1 Turnover Value

Turnover value is an important metric in management that describes the turnover value or total sales or total revenue generated by the company. Total turnover value can be obtained using Equation (1) below.

$$\text{Turnover value} = \Sigma\ (\text{Number of units} \times \text{Selling price}) \quad (1)$$

Where the number of units is the total units per product according to the demand data and the selling price is the price per product.

2.2 Clarke and Wright Savings

The Clarke and Wright Savings Method is a step discovered by Clarke and Wright in 1964 (Marpaung et al., 2022). This method serves to minimise time, cost, or distance by taking into account existing constraints. The Clarke and Wright Savings Method is the optimal solution because the Clarke and Wright Savings Method is the most widely used heuristic method for constructing routes and the total distance obtained is small (Munir et al., 2023). According to Engraini et al. (2020), the steps in the calculation process in the clarke and wright savings method are as follows.

1. Create a distance matrix, namely the distance matrix between depots and nodes and between nodes.
2. Calculate the savings value (Sij) in the form of mileage from a vehicle to serve nodes i and j combined using Equation (2) below.

$$S_{ij} = C_{oi} + C_{oj} - C_{ij} \quad (2)$$

   Where Coi is the distance from the depot to node i, Coj is the distance from the depot to node j, Cij is the distance from node i to node j, and Sij is the distance saving value from node i to node j.
3. Create a savings matrix, where the general form of the savings matrix.
4. Select the combination of nodes with the largest to smallest saving value to be included in the route.
5. Conducting route feasibility tests by calculating constraints such as the total demand volume of the selected node combinations and the total completion time. If the total demand volume is ≤ the vehicle capacity and the total completion time is ≤ the time capacity then go to step 6, but if the total demand volume is > vehicle capacity and the total completion time is > time capacity then create a new route and return to step 4 by selecting the customer combination that has the next largest savings value.

$$\text{Total demand volume} = \Sigma\ (\text{Number of units} \times (\text{Length} \times \text{Width} \times \text{Height}))_{(i)} \quad (3)$$

$$\text{Total demand weight} = \Sigma\ (\text{Number of units} \times \text{Product weight})_{(i)} \quad (4)$$

$$\text{Total completion time} = \text{Travelling time} + \text{Initial loading time} + \text{Unloading time}_{(i)} \quad (5)$$

Where i is the 1st,2nd,3rd product,... and so on.

6. Insert the selected nodes into the route.
7. Check whether all nodes have been assigned, if so then the distribution route is formed, if not then return to step 4 to select the combination of nodes with the next largest savings value.

2.2.1 Head and Tail Concept

The Head and Tail concept is used in the development of the Clarke and Wright Savings Method. The Head and Tail concept is used to change the route determination process by considering the savings value of the points that have been included in the temporary route. The steps in applying the Head and Tail concept to the Clarke and Wright Savings Method are as follows.

1. The initial head and tail are the point pairs that have the largest saving value. However, if there are pairs of points that have the same saving value, the pair of points that has the closest distance is taken.
2. Delete the selected point to continue the step.
3. Determine the next point by comparing the saving value between the point with the head and the point with the tail to determine the new point replacement. If the saving value of the point with the head is greater than the saving value of the point with the tail, then the head is replaced with a new point and vice versa.
4. Delete the selected point again to continue the step.
5. If there are still saving values with unselected points then the iteration is continued by determining the new head and tail. However, if there is no saving value left then iteration is done by restarting from determining the initial head and tail on the next vehicle route ($k = k + 1$).

2.3 Cluster First Route Second

Cluster First Route Second is a problem solving that involves two stages (Putri et al., 2021). The first stage is to group customer location points by considering capacity and distance first. Then the second stage is to determine the order of delivery within each group of customers that have been formed in order to get the optimal vehicle assignment and route. The Cluster First Route Second Method is useful for simplifying the problem by forming groups to get the optimal solution.

2.3.1 Sweep Algorithm

The Sweep Algorithm was first introduced by Gillet and Miller in 1974, which is a simple solution method used in creating clusters (Fauzi et al., 2023). Basically, this algorithm collects agents with the same direction from the distributor into one vehicle route using geographic coordinates. The steps in performing the Sweep Algorithm are as follows.

1. Create cartesian coordinates at each point,
2. Calculate the polar coordinates at each point, the calculation can be done using software such as Geo Gebra or Microsoft Excel. Polar coordinates can be done using Equation (6) below.

$$\theta_i = \arctan(\text{relative y}, \text{relative x}) \quad (6)$$

Where θ is the polar coordinate, and i is the 1st,2nd,3rd point,... and so on.

3. Sorting the smallest to largest polar coordinate value,
4. Making clustering based on the order of polar coordinates,
5. Followed by route sorting using a method that can solve the Travelling Sales Problem (TSP), for the example is Nearest Neighbor Method.

2.3.2 Nearest Neighbor

Mapping delivery routes, setting delivery schedules, and managing delivery fleets are some examples of using the Nearest Neighbor Method in distribution routes. The purpose of the Nearest Neighbor Method is to

determine the closest route or nearest neighbor from a certain location or point to optimize the distance in the process of distributing goods or services (Azhar et al., 2023). Determination of the Nearest Neighbor can be done using Equation (7) below.

$$\Delta f = d_{0i} + d_{ij} + ... + d_{j0} \quad (7)$$

Where Δf is the total distance, d0i is the distance from the starting point (warehouse) to location i, dij is the distance from location i to location j (insert nearest location), and dj0 is the distance from location j to the starting point (Octaviarie et al., 2023). The steps to determine the route using the Nearest Neighbor Method are as follows.

1. Select the center point as the starting point for delivery or departure point.
2. Determine the point with the smallest distance from the starting point then merge between the two points.
3. The last visited point becomes the starting point, and then selects the next point with the closest distance from the starting point.
4. Repeat the process until the capacity reached is insufficient to select the next point.
5. Draw the point on a line, this point is called a travel route.
6. Perform the same process, in steps one through five until all existing points have their own routes.

3. RESULT AND DISCUSSION

This research aims to optimize distribution truck routes. The research uses data for one month in August 2024. Then, calculations are carried out using Equations (3), (4), and (1) on the demand data to produce data listed in Table 1. Meanwhile, Equation (5) is used after the formation of a route so that the distribution completion time does not exceed the time limit of the truck's cooling engine capability.

Table 1. Calculated demand data for each node.

Node	Demand		
	Total Volume (m^3)	Total Weight (Ton)	Total Price (IDR)
A1	2.714	0.740	79.896.418
A2	3.655	0.936	110.162.172
A3	1.062	0.343	42.262.917
A4	1.062	0.281	38.960.451
A5	3.887	0.995	106.846.935
A6	1.135	0.292	36.500.907
A7	1.630	0.376	37.186.887

Table 2. Truck capacity.

Truck Box Dimension	(m)	Box Volume (m^3)	*Allowence* (%)	Max Load Volume (m^3)	Max Load Weight (Ton)	Cooling Engine Capability (minute)
Length	3	9.18	25	6.885	5	360
Width	1.7					
Height	1.8					

The truck capacity in Table 2 is used as constraints in this research. There are three constraints used, which consist of the volume of cargo, the weight of the cargo, and the time to complete the distribution. The value of volume of cargo taken from the maximal load volume, which is 6.885 m^3. The value of weight of cargo taken from the maximal load weight, which is 5 Ton. The value of time to complete the distribution taken from the cooling engine capability, which is 360 minutes.

3.1 Turnover Value

Turnover value is the overall accumulation of the amount of revenue earned from the sale of a product or service that is calculated as a whole over a certain period of time (Wilujeng et al., 2024). Based on calculated demand data, it can be seen that the turnover value of each node using Equation (1) is IDR 451,816,687. This value can be said to have exceeded the minimum turnover value or minimum turnover value in one out-of-town distribution trip set by the company, which is IDR 100,000,000 so that the distribution problem solving can be continued.

3.2 Clarke and Wright Savings

This method is carried out to determine the number of trucks used and the group of locations to be targeted based on constraints, namely weight capacity, volume and truck cooling engine time limit. The first step is to create a distance matrix from one node to another based on distance data which can be seen in Table 3. Then, proceed with calculating the savings matrix using Equation (2) to produce data which listed in Table 4.

Table 3. The distance matrix.

	A1	A2	A3	A4	A5	A6	A7
A1	0	105	111.5	114	117	120	120
A2	105	0	18.5	23	25	27	27
A3	111.5	18.5	0	5.2	7.7	8.9	9.7
A4	114	23	5.2	0	5.7	5.1	5.1
A5	117	25	7.7	5.7	0	3.8	5.9
A6	120	27	8.9	5.1	3.8	0	2.5
A7	120	27	9.7	5.1	5.9	2.5	0

Table 4. The saving matrix.

	A1	A2	A3	A4	A5	A6	A7
A1	0	198	196	197	198	198	198
A2	198	0	220.3	220.8	222.6	221.8	215.5
A3	196	220.3	0	225.3	228.9	228.9	222
A4	197	220.8	225.3	0	233.2	231.1	227
A5	198	222.6	228.9	233.2	0	237.5	233
A6	198	221.8	228.9	231.1	237.5	0	231
A7	198	215.5	222	227	233	231	0

Based on the calculation results in Table 4, the distribution route results are formed for route 1 with nodes G-A5-A6-A4, route 2 with nodes G-A3-A7, and route 3 with nodes G-A1-A2. Detailed results can be seen in Table 5 below.

Table 5. The Clarke and Wright Savings results.

Truck	Route	Total Volume (m^3)	Total Weight (Ton)	Total Time (minute)	Total Distance (km)
1	G-A5-A6-A4	6.083	1.568	261	128.4
2	G-A3-A7	2.692	0.720	357	229
3	G-A1-A2	6.369	1.676	237	123.5

The Clarke and Wright Savings Method only determines the route sequence by considering the savings value of the pair of two customer points only and does not consider the savings value of other pairs of customer points that have been entered previously (Yusuf and Sukoyo, 2023). Therefore, the nodes for each route were

arranged using the Head and Tail concept. The results of determining the route can be seen in the Table 6 below.

Table 6. The Head and Tail results.

Truck	Route	Total Volume (m^3)	Total Weight (Ton)	Total Time (minute)	Total Distance (km)
1	G-A4-A5-A6	6.083	1.568	253	123.3
2	G-A3-A7	2.692	0.720	357	229
3	G-A1-A2	6.369	1.676	237	123.5

Based on the calculation results in Table 6, the distribution route results are formed have changed for route 1 with nodes G-A4-A5-A6. While for other routes, there is no change in the order of nodes. This means that the previously formed nodes are optimal, except for the nodes on the first route.

3.3 Cluster First Route Second

This method is done by using a Sweep Algorithm to create clusters as an initial stage. This algorithm is used to determine the intended location group based on the constraints in the study, namely the weight capacity, volume and time limit of the truck cooling machine. The first step is to create a scatter diagram with the help of Microsoft Excel based on the coordinate data of each point.

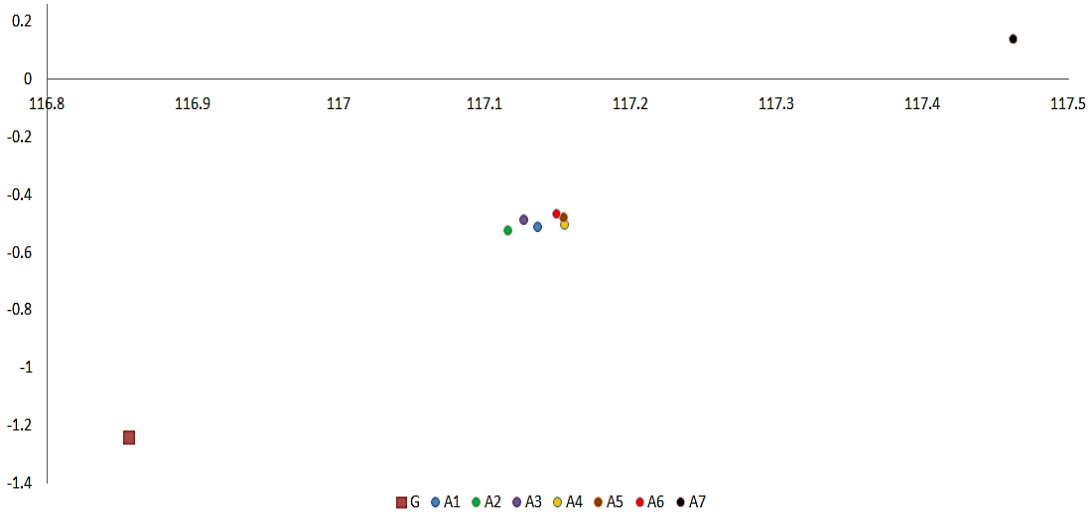

Figure 1. Scatter diagram of each nodes.

Based on the scatter diagram, it can be seen that the position of all nodes is to the right of the depot. Therefore, the polar coordinates of each point are calculated using Equation (6) sorted from the smallest to the largest value. Then, a straight line is drawn from one node to the next on the scatter diagram to see the clusters formed. This is done while still considering the three constraints.

Table 7. The Head and Tail results.

Node	θ
A3	0.342666767
A2	0.346119658
A6	0.359518442
A1	0.364152713
A5	0.370555893

A4	0.382750806
A7	0.412141791

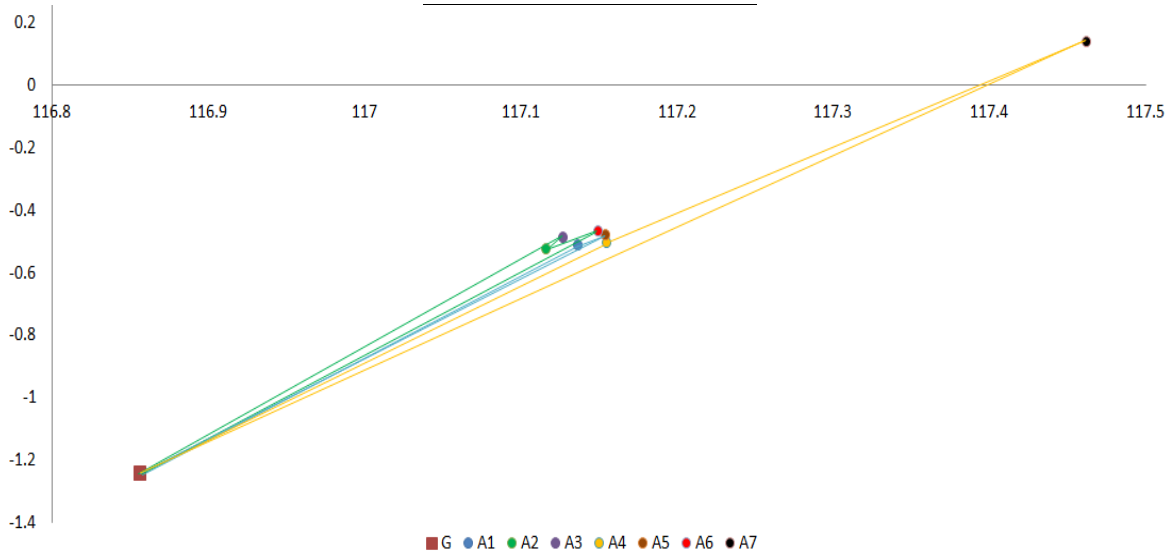

Figure 2. Clusters that are formed

.

Based on the clusters result, the distribution route results are formed for route 1 with nodes G-A3-A2-A6, route 2 with nodes G-A1-A5, and route 3 with nodes G-A4-A7. Detailed results can be seen in Table 8 below.

Table 8. The cluster results.

Truck	Route	Total Volume (m^3)	Total Weight (Ton)	Total Time (minute)	Total Distance (km)
1	G-A3-A2-A6	5.852	1.572	273	128.9
2	G-A1-A5	6.600	1.734	258	132
3	G-A4-A7	2.691	0.658	358	230

After that, route determination is carried out as the second stage using the Traveling Salesman Problem such as the Nerarest Neighbor Method. The calculation is carried out using Equation (7) and the results can be seen below.

Table 9. The routes results.

Truck	Route	Total Volume (m^3)	Total Weight (Ton)	Total Time (minute)	Total Distance (km)
1	G-A2-A3-A6	5.852	1.572	259	121.8
2	G-A1-A5	6.600	1.734	258	132
3	G-A4-A7	2.691	0.658	358	230

Based on the calculation results in Table 9, the distribution route results are formed have changed for route 1 with nodes G-A2-A6-A6. While for other routes, there is no change in the order of nodes. This means that the previously formed nodes are optimal, except for the nodes on the first route.

3.4 Result Comparison

Based on the results of each method carried out above, namely the Clarke and Wright Savings Method and the First Route Second Cluster, a comparison is made to see which method is more optimal.

Table 10. Comparison of the two methods.

Method	Quantity of Truck	Truck	Route	Total Time (minute)	Total Distance (km)
Clarke and Wright Savings	3	1	G-A4-A5-A6	253	123.3
		2	G-A3-A7	357	229
		3	G-A1-A2	237	123.5
		Grand Total		847	475.8
Cluster First Route Second	3	1	G-A2-A3-A6	259	121.8
		2	G-A1-A5	258	132
		3	G-A4-A7	358	230
		Grand Total		875	483.8

Based on this comparison, it can be seen that the total trucks used with the Clarke and Wright Savings Method and the Cluster First Route Second Method have the same number of 3 units. The total travelling time with the Clarke and Wright Savings Method is 847 minutes which is smaller than the travelling time with the Cluster First Route Second Method of 877 minutes. The total travelling distance with the Clarke and Wright Savings Method is 475.8 km which is smaller than the travelling distance with the Cluster First Route Second Method of 483.8 km. The difference in total travel time between the two methods is 28 minutes and the difference in total distance is 8 km, so the method with the shortest total travel distance and the fastest total travel time is the Clarke and Wright Savings Method followed by the Head and Tail concept.

Thus, the route determination method using the Clarke and Wright Savings Method followed by the Head and Tail concept can be considered as the most optimal route determination method compared to the Cluster First Route Second Method carried out in solving the problem in this study. Then based on the problems experienced by the company, the travel time to distribute to the farthest point (A7) lasts for 9 hours or 540 minutes can be completed with a travel time of 237 minutes. This shows that with this method the company can minimise time by 56% or equivalent to saving 303 minutes which is faster than before.

4. CONCLUSIONS

Based on the results of the analysis and discussion, it can be concluded that the number of trucks used is 3 trucks with each having 1 route generated by the Clarke and Wright savings method followed by the Head and Tail concept. The first truck route has an optimal travel time of 253 minutes and an optimal distance of 123.3 km. The second truck route has an optimal travel time of 357 minutes and an optimal distance of 229 km. The third truck route has an optimal travel time of 237 minutes and an optimal distance of 123.5 km.

The results of this study recommend the company to consider the proposed application of the Clarke and Wright Savings Method developed with the Head and Tail concept to determine routes so that the distribution process becomes more optimal. That way, the company still prioritises large partners and can reduce losses. In addition, the company still has the opportunity to maximise the use of transportation resources by adding destination location points on trucks that have load volume, load weight, and distribution completion time with values that are still below the limit.

However, this research also has limitations in processing this case study. The limitations of the research are that the demand data used is only one month in August 2024, the distance and time data does not consider traffic congestion conditions, and it does not rule out the possibility of data bias in this research. Furthermore, suggestions for future research are to consider using other methods as route sorting such as Genetic Algorithm, Insertion Method, Ant Colony Optimisation, and Branch and Bound. In addition, consider the use of other software such as Arena and Cube IQ because they can produce more real load capacity simulations to optimise the use of truck capacity.

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Analysis of Workplace Accident Risk Using The Hazard Identification Risk Assessment and Determining Control (HIRADC) Method in PMKS PT. Sisirau

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Work Accidents; HIRADC; Risk Assessment; Control; K3

Abstract

Work accidents are one of the serious problems that have a direct impact on worker safety and company productivity. This study was conducted at PMKS PT. Sisirau located in Aceh Tamiang. This research aims to explore potential sources of danger, evaluate the degree of associated threats, and formulate strategic preventive measures through the structured framework of Hazard Identification, Risk Assessment, and Control Determination (HIRADC) method. The focus of this study was on three work stations, namely loading ramp, boiling (sterilizer station), and tipler. The data used were in the form of work accident reports from January 2021 to February 2025, as well as the results of observations and interviews in the field. The results of the study showed that there were a total of 18 work activities identified as hazardous, consisting of 8 activities at the loading ramp station, 5 activities at the boiling station (sterilizer), and 5 activities at the tipler station. The results of the risk assessment showed that at the loading ramp station there were 5 activities with One activity presented moderate risk; three others showed low-risk potential. At the boiling station (sterilizer) there were 4 activities with a moderate risk and 1 activity with a low risk. Meanwhile, at the tipler station, among the evaluated activities, one was determined to involve a significant risk factor, whereas two others presented comparatively lower levels of risk, and 2 activities with low risk. Recommended risk control includes 7 activities with engineering control, 9 activities with administrative control, and 10 activities with mandatory Application of individual safety gear.

1. INTRODUCTION

Occupational Safety and Health (K3) is an effort to ensure safe, healthy, and comfortable working conditions for workers in order to reduce the likelihood of incidents and work-induced health conditions. According to the International Labor Organization (ILO), K3 plays an important role in protecting workers from various risks in the workplace and improving worker welfare. K3 Intends to elevate and sustain peak physical well-being, mental, and social health of all workers in all Committed to strengthening and protecting top physical capability. Work accidents not only affect workers but can also cause a decrease in company productivity(Parentai et al., 2025).

PMKS PT. Sisirau is a private business entity engaged in the processing of palm oil (CPO). This company also produces kernels (fruit cores) and shells. PMKS PT. Sisirau is located in Sidodadi Village, Vocational Youth District, Aceh Tamiang Regency. PMKS PT. Sisirau has 12 interconnected work stations starting from the fruit receiving station (weight bridge station), sorting station, loading ramp station, boiling station (sterilizer station), tipler station, threshing station, pressing station, purification station (clarification station), kernel processing station, water treatment station, boiler station, and waste station. PMKS PT. Sisirau has a production capacity of 30 tons of FFB/hour(Subandri & Prabowo, 2020).

The work stations that are the focus of this study are the loading ramp station, the boiling station (sterilizer station) and the tipler station, where all three have high potential risks to occupational safety and health (K3).

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Based on work accident data from January 2021 to February 2025, there have been 30 cases of work accidents spread across the three stations, namely, 13 cases at the loading ramp station, 9 cases at the boiling station (sterilizer station), and 8 cases at the tipler station. These work accidents occur due to several causes such as being hit by TBS when pouring into a lorry, being hit by a rope sling, being caught by a bucket loader, burns due to steam spray from the sterilizer, being bounced by a broken rope and falling while climbing stairs to open the hydraulic door. In addition to the accidents that have occurred, observations in the field also show that there are working conditions that can cause accidents such as Staff members who ignore PPE usage, inadequate infrastructure such as sloping stairs without handrails, and uneven rail conditions because they are stacked with new rails. From the problems above, the author aims to analyze the occupational safety and health risks that occur in the work area using The HIRADC approach to identifying hazards, assessing risks, and establishing controls. HIRADC is a systematic method used to identify hazards, assess the level of risk posed by the hazard, and determine the most appropriate control to reduce or eliminate the risk, with the aim of creating a safer and healthier work environment. Based on the existing problems, the author is interested in conducting a study entitled "Analysis of Work Accident Risks Using the Hazard Identification Risk Assessment and Determining Control (HIRADC) Method at PMKS PT. Sisirau."

The objective of this study is to establish the identification of occupational accident hazards at the loading ramp station, boiling station (sterilizer station) and tipler station at PMKS PT. Sisirau. To determine the results of the assessment of occupational accident risks at the loading ramp station, boiling station (sterilizer station) and tipler station at PMKS PT. Sisirau. To determine the efforts to control occupational accident risks that can be applied at the loading ramp station, boiling station (sterilizer station) and tipler station at PMKS PT. Sisirau.

Maintaining a safe and healthy work environment is an approach used to improve overall working conditions. The goal of this effort is to ensure employees stay physically fit, mentally stable, and socially balanced to handle all forms of occupational tasks effectively(Kurnia & Apsari, 2023). Occupational health in general can be defined as a condition in which workers are in good health without experiencing illness, injury, or damage to body parts while in the work environment(Ahnaf, 2024).Risk is defined as how often a hazardous incident or exposure occurs that can cause injury or health problems of a certain severity due to an event. Risk is an event or condition that can hinder the achievement of company goals and targets(Anizar & Fandya, 2022). A job-site accident is considered an unanticipated and unpredictable event that can result in material and physical losses for the individuals involved. These accidents often occur when several factors interact simultaneously in the work environment or in the production process. Thus, work accidents do not occur in isolation, but rather as a result of a combination of several existing factors.(Sulistyaningtyas, 2025).

2. METHOD

2.1 Data Types and Sources

Primary data is information obtained through direct observation in the field. In this study, the primary data used is data from direct observation and interviews with workers. Secondary data is data obtained directly collected from several sources.

In this study, the secondary data used were work accident recapitulation data, production processes, and literature studies.(Ariana et al., 2025).

2.2 Analysis Method

The analysis method is the steps taken to study and process data. In this study, the analysis method used is as follows:

1. Identifying hazards that can cause work accidents during the production process in the worker's environment.(Gufron & Rusindiyanto, 2025). The hazard identification process was carried out through direct field observations, interviews with experienced workers, and consultations with the K3 (Occupational Health and Safety) team. A structured checklist based on ISO 45001 and standard operating procedures from the company was used to ensure consistency and objectivity in identifying potential

hazards. Validation of findings was conducted jointly with the supervisor and safety officer to minimize bias and subjectivity (Farras et al., 2025).

2. Risk assessment of work accidents with a likelihood scale that shows the frequency with which an accident might occur and the level of harm it could result in. The values of likelihood and severity will then be used to compile the risk matrix.(Saputro & Lombardo, 2021). The risk assessment process in this study uses a risk matrix based on the product of Likelihood (L) and Severity (S) values. Likelihood refers to the probability of a hazard occurring, while Severity indicates the potential impact of the incident. The scoring scale adopted in this study is based on the Occupational Safety and Health Administration (OSHA) guidelines and Indonesian Ministry of Manpower Regulation (Permenaker No. 5/2018), as follows:
   a. Likelihood
      Indicates how likely an accident is to occur. According to the AS/NZS 4360 standard, likelihood is categorized within a range from risks that are rare to those that may occur at any time. Likelihood refers to the frequency or probability of a hazardous event occurring. The scale of possible values can be seen in Table 1 as follows:

Table 1 Likelihood Values

Values	***Likelihood***	**Information**
5	A *Almost Certain*	Occurs in almost all circumstances, for example, occurs once a day in a year
4	B *Likely*	Very likely to happen, for example once a week in a year
3	C *Possible*	It can happen at any time, for example once a month in a year.
2	D *Unlikely*	It may happen at any time, for example once every six months of the year.
1	E *Rare*	It can only occur under certain circumstances, for example, it occurs more than once every six months in a year.

Source: AS/NZS Standard 4360

   b. Severity
      Severity indicates the level of severity or consequences resulting from a risk. Severity or consequence indicates the severity of the impact of the accident. Severity is a measure of the possible consequences or impact of a work accident. This severity scale helps determine the overall risk level by combining it with the likelihood of the incident occurring. The results are used to prioritize risk control. The severity scale can be seen in Table 2 below:

Table 2. Severity Values

Mark	*Severity*	Information
1	*Insignificant*	The incident did not result in any physical loss or injury, and did not result in any lost work days.
2	*Minor*	Incidents can result in minor injuries, sprains, bruises and require first aid, but can still work the same day.
3	*Moderate*	Incidents can result in moderate injuries, lacerations, burns and require medical treatment, loss of 3 days of work time.
4	*Major*	Incidents can result in serious injury, severe cuts, broken bones, blisters, loss of more than 3 days of work.
5	*Catastrophic*	Resulting in physical disability, death, loss of long or even permanent work days.

Source: AS/NZS Standard 4360

To obtain the risk value, it is calculated using the following risk assessment formula:
Formula:
Risk = L x S
Information:
R : Accident Risk
L : The probability of an accident occurring
S :Severity of accident

c. Risk Value Matrix

*Risk matrix*is a value that indicates the level of risk based on a scale of likelihood and severity. The grouping according to the level of risk value can be seen in Table 3 as follows:

Table 3. Risk Level Grouping

Risk Level	Action
Extreme	15-25 Disasters, require the involvement of leaders for control in accordance with the control hierarchy.
High	10-14 Unacceptable risks involving work units
Medium	5-9 Risk is acceptable, monitoring is carried out up to the head of the department
Low	1-4 Monitoring is required to ensure existing controls are maintained and implemented (control with routine procedures)

Source: AS/NZS Standard 4360

3. Determining risk control To eliminate and respond to hazards to stop repeated occurrences. Risk control can be done via the hierarchy of controls eliminating and substituting risks, employing engineering designs, administrative protocols, and PPE usage.(Ramadhania et al., 2021).

2.3 Limitations on Data Availability

This study relied primarily on recorded work accident data from January 2021 to February 2025 at PMKS PT. Sisirau. However, near-miss incidents, unsafe conditions, and behavior-based safety (BBS) observations were not systematically documented during the study period. The absence of such data introduces potential bias, since the risk profile is based only on incidents that were formally reported. As a result, the analysis may underestimate hazards that occur frequently but do not result in recordable accidents.

To address this limitation, future research should integrate near-miss reporting systems and structured safety observations into the HIRADC process. Collecting such data over a 3–6 month period would provide a more comprehensive picture of workplace risks and improve the accuracy of the risk assessment. The implementation of behavior-based safety (BBS) monitoring is also recommended to capture unsafe acts and conditions that might otherwise be overlooked.

2.4 Assessor and Reliability

The risk assessment was conducted by three assessors consisting of one researcher and two safety officers from PMKS PT. Sisirau. Prior to the assessment, a short briefing session was conducted to ensure that all assessors applied the same interpretation of likelihood and severity scales. To improve consistency, the assessors carried out the scoring independently and then discussed discrepancies until consensus was achieved.

Although formal statistical measures of inter-rater reliability such as Cohen's Kappa were not calculated, this consensus approach helped to reduce subjective bias in risk ranking. In future studies, the use of structured reliability metrics is recommended to quantitatively evaluate the level of agreement among assessors(Subandri & Prabowo, 2020).

3. RESULTS AND DISCUSSION

3.1 Hazard Identification Risk Assessment And Control At Loading Ramp Station

The results of hazard identification, risk assessment and risk control at the loading ramp station can be examined in Table 4 as follows:

Table 4. Results of Hazard Identification, Assessment and Control at Loading Ramp Stations

No	Work Activities	Hazard	Risk	L	S	Risk Value	Determining Control
1	Opening and closing the Hydraulic Door of loading ramp	Hit by TBS that fell from a crane	Broken neck	2	4	8	*Administrativ,* PPE
2	Climb the ladder to open the hydraulic door	Fell down the stairs because there was no handrail	Bruises on the legs	1	2	2	*Engineering*
3	Passing through the rail area to monitor the lorry	Stumbled upon an uneven rail	Laceration on the leg	2	3	6	*Engineering*

4	New lorry replacement process	Stuck in loader bucket while unloading lorry	Fracture of the arm	1	4	4	*Administrative*
5	Attach the swing rope to the capstan post	Tripped over capstan safety pole	Laceration on the leg	2	3	6	*Administrative*
6	The process of inserting fallen fruit using a tojok tool into the lorry	Hit by a corner while loading TBS into a truck	Broken leg, laceration on the leg	2	4	8	*Administrative*
7	Attachment of rope to lorry hook	Hands trapped while adjusting the rope to the lorry hook	Bruises on the hands	1	2	2	PPE
8	Pulling out the stuck TBS	Affected by TBS	Laceration on the arm	2	3	6	PPE

3.2 Hazard Identification, Risk Assessment and Control at Boiling Station (Sterilizer Station)

The results of hazard identification, risk assessment and risk control at the boiling station (sterilizer station) can be seen in Table 5 as follows:

Table 5. Results of Hazard Identification, Assessment and Control at the Boiling Station (Sterilizer Station)

No	Work Activities	Hazard	Risk	L	S	Risk Value	Determining Control
1	Opening and closing the sterilizer door	Fell while opening the door because the floor was slippery	Laceration on the leg	2	3	6	*Engineering,*PPE
2	The process of checking TBS in the sterilizer	Exposure to hot steam (steam)	Burns on the skin	2	3	6	*Administrative*, PPE
3	Attaching the sling to the lorry that will enter the sterilizer	The rope bounced	Bruises on the body	1	2	2	*Administrative*, PPE
4	Opening the sterilizer door after the boiling process	Steam (hot steam)	Blisters, burns on the skin	2	4	8	*Administrative*, PPE

No	Work Activities	Hazard	Risk	L	S	Risk Value	Determining Control
5	Cleaning the sterilizer area after boiling	Stuck in a puddle of condensate water	Laceration on the leg	2	3	6	*Engineering*

3.3 Hazard Identification Risk Assessment And Control At Tipler Station

The results of Spotting workplace hazards, measuring associated risks, and enforcing control action at the Tipler station can be seen in Table 6 as follows:

Table 6. Results of Hazard Identification, Risk Assessment and Control at Tipler

No	Work Activities	*Hazard*	Risk	L	S	Risk Value	Determining Control
1	Operating the tipper machine	Exposed to hot steam from the lorry when it was being turned on the tipper	Burns on the skin	2	3	6	PPE
2	Pulling the rope	Hit by a rope	Laceration on the arm	2	3	6	*Engineering*, PPE
3	Controlling the tipler machine	Slipped while walking around the machine due to slippery floor	Sprained ankle	1	2	2	*Engineering*
4	Push/pull the lorry towards the transfer carriage	Body trapped between lorry and transfer carriage frame	Lacerations on the body	1	3	3	*Administrative*, PPE
5	Passing the work area while the lorry is moving	Hit by a lorry due to blind spot when the lorry was moving	Physical disability hit the spine	2	5	10	*Engineering, Administrative*

3.4 Risk Drivers per Workstation

The summarizes the main risk drivers identified in each workstation of the palm oil mill. The synthesis highlights not only the highest-ranked risks but also the dominant type of control applied at each location,can be seen in Table 7 as follows:

Table 7. Summarizes The Main Risks In Each Workstation

Workstation	Highest Risk Identified	Dominant Control Applied	Priority Level
Loading Ramp	Opening and closing the Hydraulic Door of loading ramp	*Administrative/*PPE	Medium
Sterilizer	Opening the sterilizer door after the boiling process	*Administrative/*PPE	Medium
Tipler	Passing the work area while the lorry is moving	*Engineering/Administrative*	High

The synthesis in Table 7 shows that the loading ramp and sterilizer stations both present medium-level risks. At the loading ramp, the highest risk arises from the activity of opening and closing the hydraulic door, which requires strict compliance with administrative measures and the consistent use of PPE to prevent potential crushing and falling hazards. Similarly, at the sterilizer, opening the door after the boiling process remains a critical task that also relies heavily on administrative control and PPE, particularly to protect workers from exposure to hot steam and pressurized equipment(Caesar et al., 2023).

In contrast, the tippler station demonstrates a higher priority level due to the danger of workers passing through the area while the lorry is moving. This mechanical hazard demands not only administrative controls but also engineering measures, such as improved traffic management and physical barriers, to reduce accident potential.

Overall, the findings indicate that while all stations require ongoing monitoring, the tippler station should be prioritized for risk control improvements, followed by strengthening of safe practices at the loading ramp and sterilizer stations(Nugraha & Yulia, 2021).

3.5 Control Options and Feasibility Considerations

For the prioritized risks identified, several options of higher-level control measures were considered. At the loading ramp, the use of mechanized unloading equipment (engineering control) could significantly reduce manual handling risks. However, this option is currently constrained by economic factors, as the investment cost for mechanization is relatively high compared to the current scale of operations. As an interim solution, administrative controls and consistent use of PPE remain the main strategies, while gradual implementation of mechanization can be planned for future upgrades.

1. At the sterilizer station, eliminating or substituting the process of manual door opening is technically challenging due to the design of the existing facility. Installing automatic door systems (engineering control) would be an effective solution, but it requires substantial capital expenditure and downtime for retrofitting. Consequently, administrative controls, strict SOPs, and PPE are prioritized while a long-term plan for equipment modernization is proposed(Ilmi, 2025).
2. For the tippler station, engineering controls such as traffic management systems, physical barriers, and warning alarms can reduce hazards associated with moving lorries. While some measures are feasible, full implementation is limited by space constraints and the need to maintain production flow. Therefore, administrative controls are maintained alongside partial engineering solutions(Ihsan et al., 2025).
3. To ensure effectiveness, a monitoring framework combining leading indicators (eg, frequency of safety inspections, training participation rate, observation of unsafe acts/conditions) and lagging indicators (eg,

accident frequency rate, number of near-miss reports) will be applied. This dual approach enables early detection of unsafe conditions while also tracking the outcomes of implemented controls(Palaniandy et al., 2020).

3.6 Discussion

The analysis using A systematic method for identifying workplace dangers, assessing potential risks, and establishing appropriate controls (HIRADC) method at the loading ramp station, boiling station (sterilizer station) and tipler is as follows:

1. The discussion of this study focuses on interpreting the findings across three workstations loading ramp, sterilizer, and tipler by comparing the level of risk and the types of control required. The loading ramp station showed the highest number of hazardous activities eight, mostly related to physical hazards such as being hit by objects or slipping due to uneven surfaces. Meanwhile, the sterilizer station involved five hazardous activities, mainly associated with exposure to hot steam and slippery work conditions, resulting in a moderate risk level. The tipler station identified five hazardous activities as well, including one with a high-risk level due to the movement of heavy machinery and poor visibility blind spots.
2. These differences reflect how the nature of work activities and environmental factors influence the types and severity of risks in each station. For example, the loading ramp requires stronger engineering interventions, such as redesigning stairs and improving walkways, while the sterilizer station needs improved administrative control and consistent use of PPE due to the presence of heat and steam. The tipler station, where machinery is actively moving, must emphasize hazard awareness and engineering control, such as barriers and warning signs(Hasiany et al., 2024).
3. These findings are consistent with previous studies by(Ramadhania et al., 2021)who emphasized the importance of tailoring hazard control efforts to the specific context of each work activity. The application of the HIRADC method in this study provided a structured approach to identify hazards, evaluate their risks, and recommend relevant control measures aligned with occupational safety standards such as ISO 45001 and national K3 regulations(Ariana et al., 2025).
4. This study has some limitations. The risk assessment primarily focuses on reported accidents and field observations, which may not fully capture near-miss events or unsafe conditions that haven't resulted in incidents yet. Additionally, this research only focused on three workstations, and did not include other parts of the production process such as pressing or kernel processing stations. For future studies, it is recommended to incorporate real-time monitoring tools, involve more comprehensive hazard tracking, and evaluate psychological or ergonomic factors that might contribute to workplace risk(Budiman et al., 2025).

4. CONCLUSION

This study concludes that the application of the HIRADC method at PMKS PT. Sisirau successfully identified 18 hazardous work activities across three key workstations. The loading ramp station has five medium risk and three low risk activities. The sterilizer station recorded four medium-risk and one low risk activities, while the tipler station showed one high-risk, two medium-risk, and two low risk activities. The most common control measures recommended include engineering controls 7 activities, administrative controls 9 activities, and the use of personal protective equipment PPE in 10 activities. These findings demonstrate the need for targeted risk control strategies tailored to the nature of each workstation's hazard profile. The practical contribution of this research lies in its structured approach to workplace hazard identification, prioritization, and control planning using HIRADC. This framework provides clear guidance for palm oil mills in enhancing occupational safety performance and complying with national and international safety standards. The study has certain limitations. The assessment did not include near-miss events, and it focused only on three specific workstations. Broader research covering more operational units and incorporating ergonomic or psychological hazards would enhance the generalizability of the findings. Future

studies may also integrate real-time data collection methods and digital risk monitoring tools to support predictive safety management.

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Selection of Primary Land Transportation Fleet Using Vehicle Operational Cost (VOC) Method in Logistics Companies

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Logistics; Vehicle Operating Cost (VOC); Investment Feasibility

Abstract

The selection of transportation fleets plays a crucial role in determining the cost efficiency of logistics operations. This study aims to evaluate the feasibility of investing in company-owned vehicles compared to using third-party rental services on the Bandung–KTSH route operated by PT X. Using a quantitative approach with a causal associative design, this research applies the Vehicle Operating Cost (VOC) method supported by investment feasibility analysis tools including Cash Flow, Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP). The analysis shows that the average daily operational cost of company-owned vehicles reaches IDR 1.904.479, which is higher than the rental cost of IDR 1.865.385 per day. Additionally, the results show a negative NPV (-IDR 344.739.419), negative IRR (–11%), and an unattainable payback period within the 5-year investment horizon. Therefore, it is concluded that using leased vehicles is more cost-efficient than investing in company-owned trucks for this specific route.

1. INTRODUCTION

Transportation is an integral part of logistics, where transportation plays a role in transporting goods from one place to another (Qureshi & Abudllah, 2013). Logistics also plays an important role in the supply chain, especially in the distribution process of goods (Tare et al., 2024). In recent years, consumption patterns and logistics have changed along with economic development and a gradual increase in national income (Chen et al., 2016). This needs to be supported by the fleet used by the company to carry out these distribution activities. In using a delivery fleet, the company has two considerations, namely providing its own fleet or through a third party, in this case a truck vendor company (Kastella et al., 2024).

PT X is a subsidiary of PT Pos Indonesia, the business process of PT X, especially the Bandung Branch Office, is the delivery of primary goods (Bandung-KTSH) and secondary (Bandung-All PT X Hubs in Java) from PT Pos or postal goods. All postal goods deliveries are centered at the MPC (mail processing center) owned by PT Pos Indonesia in Bandung. Due to the routine delivery schedule every day, PT X uses several fleets available at the company. The fleet consists of 5 private fleets and 8 rental fleets. The goods delivery activity or shipments on the Bandung-KTSH route are transported using private fleets with an average tonnage or weight of of 4.2 to 6.7 tons per day with a FUSO fleet capacity of 8 to 12 tons. The data shows that the fleet's loading capacity is still not fully utilized.

When viewed from the cost and utility side of the vehicle, it is very ineffective. So, another alternative is to rent a CDD vehicle for the KTSH-Bandung route, and allocate Fuso on this route to be used for other operations. In line with this, research by Lindsey & Mahmassani (2017) considers the use of third party logistics (3PL) services in providing a delivery fleet, to increase vehicle utility at a more economical cost.

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From this background, this study aims to compare company-owned vehicles with rental vehicles, through the calculation of Vehicle Operating Costs (VOC) on company vehicles and the calculation of rental costs.

2. LITERATURE REVIEW

2.1 Transportation and Logistics

In the 1960s to 1970s, science related to transportation began to develop, transportation refers to public transportation and traffic, while logistics is considered a new field related to the physical delivery of goods and inventory management. In the 1980s there was the first research related to trucking, namely on the use of trains and ships for shipping goods. In the 1990s, transportation began to develop to include users (people) and goods, and in the 2000s, it began to develop along with the use of technology (Speranza, 2018). According to Jacobs (2018) transportation is the movement of people or goods from one place to another within a certain period of time using a tool driven by humans, animals, or machines. Broadly speaking, transportation is divided into three, namely land, water, and air transportation (Jacobs, 2018). Meanwhile, according to The Council of Logistics Management (CLM), Logistics is an element in supply chain management that focuses on planning, implementing, and controlling the flow and storage of goods, services, and related information efficiently and effectively, both in forward and reverse distribution flows, from the point of origin to the point of consumption, to ensure that customer needs are met (Neeraja et al., 2014).

2.2 Type of Transportation

Jacobs (2018) explains that there are six modes of transportation that are widely known by the public, namely: highway (truck), water (ship), air (plane), train (train), pipeline, and hand delivery. These types of transportation modes are suitable for handling certain types of commodities. The types of transportation modes according to Jacobs (2018) are as follows:

1. Road transport mode, some products move without some road transport. This type of mode offers great flexibility to move goods, almost any location that is not separated by water. Product size, maximum weight, and liquid or bulk can all be accommodated by this mode.
2. Water transport (ship) has a very high capacity and very low cost, but the transit time is slow, and because of the large area of shipping is not directly accessible for shipping using ship transport. This mode is very useful for most commodities such as oil, coal, and chemical products.
3. Air transport is fast but expensive. Small, light, expensive commodities are best suited for this mode of transport.
4. This mode of rail transport is a relatively cheap alternative, but each transit can take a long time. The suitability of the tracks can vary depending on the rail infrastructure.
5. Pipeline transportation, highly specialized and limited such as liquids, gases, and solids in slurry form. No packaging required and low cost per mile. Initial cost to build a pipeline is very high.

2.3 Vendor

According to Agriyantari (2014), vendors or suppliers are companies that provide services to companies, suppliers can function as distributors of goods. Choosing the wrong vendor can worsen the position of the entire supply chain process, finance and operations of the company. Customer complaints will increase and in some types of businesses, customers will give financial penalties. Vendor selection needs to be managed properly because it will determine competent vendors (Gaubert et al., 2024).

2.4 Vehicle Operating Costs (VOC)

Vehicle operating costs are important costs. Improvements or enhancements to the quality of transportation infrastructure and facilities are mostly aimed at reducing these costs. Vehicle operating costs include the use of fuel, lubricants, replacement costs (tires), vehicle maintenance costs, and driver wages or salaries (Ofyar in Yusi, 2014). Vehicle operating costs according to Lee et al. (2023) are all vehicle costs borne by the vehicle owner.

Insurance costs do not include vehicle operating costs because they are calculated as accident costs. The first four cost factors mentioned above are usually a function of speed. At low speeds, if the speed is increased, this cost will decrease until it reaches a minimum (at a relatively low speed) and then increase continuously after passing the relatively low speed limit. So, improving the transportation system by increasing the average speed can increase operating costs. The case of speed reduction caused by traffic congestion is an exception. The study of VOC calculation consists of the sum of fixed vehicle costs, variable costs and overhead costs. The equation is as follows

VOC = Fixed Cost + Variable Cost + Overhead Cost .....(1)

(1.) Fixed Costs

According to Rudianto (in Yusi, 2014) Fixed costs are costs that will relatively not change even if there is a change in the level of activity within certain limits. Fixed costs consist of vehicle depreciation costs, vehicle tax costs and vehicle crew salary costs.

(2.) Variable Costs

Variable costs are costs incurred when the vehicle is operating. Variable costs are often also referred to as variable costs, because these costs vary greatly depending on the results produced. Variable costs include fuel costs, service costs, spare part costs, other usage costs, etc.

(3.) Overhead Costs

According to Rudianto (2013) overhead costs are the costs of direct raw materials and direct labor but are still needed in the production process. Overhead costs are partly variable costs and partly fixed costs. Vehicle overhead costs are defined as indirect materials, Loading and Unloading Labor, and other costs that are not easily defined or charged directly to a job, production results, or the final destination of certain costs such as government contracts. Some researchers do it in 2 ways, namely:

a. Calculate 20-25% of the total fixed costs and variable costs
b. Calculating overhead costs in detail, namely calculating overhead costs that need to be monitored periodically by vehicle owners.

2.5 Cash Flow Projection

According to Miro (2008) Cash Flow provides an assessment of investment programs for the next few years. In this case, when compared to saving money in a bank, the value of investment money poured into a project in the next nth year, its value will be greater but in year 0, it is only a cost with a profit level of 0 (zero).

2.6 Net Present Value (NPV)

According to Bubeck et al. (2016), the Net Present Value (NPV) is calculated using the following formula:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} - \sum_{t=0}^{n} \frac{Co_t}{(1+i)^t}$$

Keterangan:

(C)t	: Cash inflow in year t
(Co)t	: Cash outflow or payment in year t
n	: Lifespan of the unit/business
i	: Discount rate
t	: Year

2.7 Internal Rate of Return (IRR)

According to Baldric Siregar (2013), IRR is defined as the interest rate that determines the present value of the project's cash inflows equal to the present value of the project's costs. In other words, IRR is the interest rate that makes the project's NPV equal to zero. The formula used to calculate IRR is:

IRR = $i1$ – NPV1/(NPV1-NPV2) ($i2 - i1$) ..... (3)

Where :
$i1$ = most attractive interest rate
$i2$ = trial interest rate
NPV1 = initial NPV
NPV2 = NPV on $i2$

2.8 Pay Back Period (PBP)

According to Slamet (2009), PBP is the length of time used by a project to be able to recoup its initial investment. PBP can be said to be feasible by the company if the return period for the investment capital is returned quickly, while PBP can be said to be unfeasible by the company if the return period for the investment capital is not fast. PBP is used to find out how long the project can be formulated as follows

PBP = investment/(annual benefit) x time period .....(4)

Where :
• Faster payback period = worthy
• Longer payback period = not worthy

3. METHOD

This study uses a quantitative approach with a causal associative research type, which aims to analyze the cause-and-effect relationship between the variables studied. The data collection method is carried out through a survey, while the problem-solving approach used is the Vehicle Operational Cost (VOC) method, which is used to assess whether vehicle investment provides benefits or losses for the company. To support the analysis of investment feasibility, Cash Flow, Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP) calculations are used to evaluate whether the company's vehicle fleet investment can be categorized as a financially feasible investment or not. All data used in this analysis were obtained through in-depth interviews with operational staff and drivers, as well as secondary data provided by PT X Branch Office Bandung. This combination of primary and internal company data ensures that the findings are grounded in actual field conditions and reflect the operational realities of the logistics process.

4. RESULT AND DISCUSSION

RESULT

4.1 Vehicle Operational Cost (VOC) Analysis

VOC calculations are divided into three parts, namely VOC based on fixed costs, non-fixed costs and others, in more detail as follows:

4.1.1 Fixed costs

- Vehicle Depreciation Costs
- New vehicle prices = IDR 621.000.000
- Residual value = 32,04 %
- Number of working days/year = 365 days
- Economic life of the vehicle (n) = 5 years

4.1.1.1 Vehicle depreciation cost/year

$$= \frac{Vehicle\ prices - (residual\ value\ x\ vehicle\ prices)}{Economic\ life\ of\ the\ vehicle}$$

$$= \frac{Rp\ 621.000.000 - (32{,}04\ x\ Rp\ 621.000.000)}{5}$$

= IDR 84.406.320 / year

4.1.1.2 Vehicle Installment Interest

- Loan (Vehicle price) = IDR 621.000.000
- Loan Term = 5 years
- Interest Rate = 31%

Capital Installment/year = Capital Interest + $\frac{principal\ debt}{loan\ term}$

- Principal debt

  = Vehicle price – Residual value

  = IDR 621.000.000 – IDR 84.406.320

  = IDR 536.593.680

- Capital installment/year

  = Capital interest + (principal debt)/(loan term)

  = 31% + (IDR 536,593,680)/5

  = IDR 33.268.808

4.1.1.3 Vehicle Crew Salaries

- Vehicle crew salary/month = IDR 3.339.580
- Number of vehicle crew = 2 drivers

Vehicle crew salary/year

= Salary/month x 13 (with THR)

= IDR 6.679.160 x 13

= IDR 86.829.080

4.1.1.4 Vehicle Crew Work Accident Insurance

Insurance Premium/Month : 1.27%

Insurance Fee/Month

= Vehicle crew salary (2 people) x 1.27%

= IDR 6,679,160 x 1.27%

= IDR 84.825

From the VOC calculations above, they are summarized in the following table 1:

Table 1. VOC Based on Fixed Costs

Type of Fee	Total Cost
Vehicle Depreciation Cost/Year	IDR 84.406.320
Capital Interest/Year	IDR 33.268.808
Vehicle Insurance	IDR 8.259.000
Vehicle Crew Salary (2 people)/Year	IDR 86.829.080
Work Accident Insurance/Year	IDR 1.017.900
Examination Test Fee/Year	IDR 910.000
Vehicle Tax Fee/Year	IDR 944.200
Total Fixed Costs/Year	**IDR 215.635.308**
Total Fixed Cost/Month	**IDR 17.969.609**
Fixed Cost Amount/Day	**IDR 691.138**

Source : Author Analysis, 2025.

From table 1 above, the VOC results based on fixed costs per year are IDR 215.635.308 while per month it is IDR 17.969.609 and IDR 691.138/day.

4.1.2 Variable Costs

4.1.2.1 Fuel usage costs

- Fuel price/liter (diesel) : IDR 5.150
- Km-mileage/day : 420 km
- Fuel usage : 6 km/liter

- **Average fuel used/day**
  = Distance traveled/day : distance traveled per liter of fuel
  = 420 km : 6 km/liter
  = 70 liters/day

- **Fuel cost/day**
  = Fuel usage/day x Fuel price
  = 70 x IDR 6.500 (diesel)
  = IDR 455.000

4.1.2.2 Tire purchase costs

- Tire usage amount : 6 Fruits
- Tire Durability : 50.000 km
- Tire Price/Piece : IDR 2.100.000

- **Tire cost/km**

$$= \frac{\text{Tire price x Tire usage amount}}{Tire\ durability}$$

$$= \frac{\text{IDR 2.100.000 x 6}}{50.000\ km}$$

= IDR 252

- **Tire cost/day**

= Tire cost/km x Distance traveled/Day
= IDR 252 x 420 km
= IDR 105.840

4.1.2.3 Minor Service Fee

Minor service is carried out every: 5000 km

Cost per small service:

• Engine Oil	: 10 ltr x IDR 32.500/ltr = IDR 325.000
• Fat 0.50kg	= IDR 35.000
• Brake Fluid 0.3 ltr	= IDR 18.000
• Service Fee	= IDR 25.000
Amount	**= IDR 403,000**

- **Small service cost/km**

$$= \frac{Total\ cost\ per\ small\ service}{Km\ everytime\ service}$$

$$= \frac{\text{IDR 403.000}}{5000\ km}$$

= IDR 81

- **Small service fee/day**

= Minor Service Cost/km x Mileage/Day
= IDR 81 x 420 km
= IDR 34.020

4.1.2.4 High service costs

Major service is carried out every 50.000 km, the cost per major service is:

• Engine oil	: 10 ltr x IDR 32.500/ltr	= IDR 325.000
• Gear Oil	: 5 ltr x IDR 30.000/liter	= IDR 150.000
• Transmission Oil	: 5 ltr x IDR 33.000/ltr	= IDR 165.000
• Fat 0.50 kg		= IDR 35.000
• Brake Fluid 0.25 ltr		= IDR 18.000
• Oil Filter 1 piece		= IDR 136.000
• Service Fee		= IDR 100.000
Amount		**= IDR 929.000**

- **Major service cost/km**
  $= \frac{Total\ cost\ per\ small\ service}{Km\ everytime\ service}$
  $= \frac{\text{IDR } 929.000}{50.000\ km}$
  = IDR 19

- **Major service fee/day**
  = Major Service Cost/km x Distance Traveled/day
  = IDR 19 x 420 km
  = IDR 7.980

From the results of the VOC calculation based on variable costs, it is summarized in the following table 2:

Table 2. VOC Accumulation based on Variable Costs

Type of Fee	Total Cost
Fuel Cost/Year	IDR 141.960.000
Tire Cost/Year	IDR 33.022.080
Small Service Fee/Year	IDR 10.614.240
Major Service Fee/Year	IDR 2.489.760
Total Variable Costs/Year	**IDR 188.086.080**
Total Variable Costs/Month	**IDR 15.673.840**
Total Variable Costs/Day	**IDR 602.840**

Source : Author Analysis, 2025.

From table 2 above, it can be seen that the VOC every year is IDR 188.086.080, every month is IDR 15.673.840 and per day is IDR 602.840.

4.1.3 Miscellaneous expense

- Meal/trip money = 2 (people) x IDR 45.000
- Parking/trip fee = IDR 30.000
- Toll/trip money = IDR 485.000
- Unforeseen expenses = IDR 100.000

Amount = IDR 705.000 (per day)

4.1.4 VOC/year

= Fixed costs + Variable costs + Other costs
= IDR 215.635.308 + IDR 188.086.080 + 219.960.000
= IDR 623.681.388

4.1.5 VOC/month

= IDR 623.681.388 : 12
= IDR 51.973.449

4.1.6 VOC/day

= IDR 51.973/449 : 26 working days
= IDR 1.998.978

4.1.7 VOC/km

= IDR 1.998.978 : 420 km (distance traveled per day)

From the calculation of all VOC above, it can be concluded in the following table 3:

Table 3. VOC accumulation

Total Fixed Cost/Year	IDR 215.635.308
Total Variable Cost/Year	IDR 188.086.080
Total Other Costs/Year	IDR 219.960.000
Vehicle Operating Cost/Year	IDR 623.681.388
Vehicle Operating Cost/Month	IDR 51.973.449
Vehicle Operating Cost/Day	IDR 1.998.978
Vehicle Operating Cost/Km	IDR 4.759

Source : Author Analysis, 2025.

4.2 Cash Flow Analysis

The cash flow analysis for fleet investment by the company is as follows:

Table 4. Cash Flow

Year	0	1	2	3	4	5
			a. Cash inflow			
Income	IDR 0	IDR 611.486.112	IDR 621.680.335	IDR 632.096.502	IDR 642.740.394	IDR 653.617.958
Sub-Total	IDR 0	IDR 611.486.112	IDR 621.680.335	IDR 632.096.502	IDR 642.740.394	IDR 653.617.958
			b. Cash out			
Initial investment	IDR 621.000.000					
Fixed costs		IDR 215.635.308	IDR 215.635.308	IDR 215.635.308	IDR 215.635.308	IDR 215.635.308
Variable costs		IDR 188.086.080	IDR 188.086.080	IDR 188.086.080	IDR 188.086.080	IDR 188.086.080
Miscellaneous expense		IDR 219.960.000	IDR 219.960.000	IDR 219.960.000	IDR 219.960.000	IDR 219.960.000
Sub-Total		IDR 623.681.388	IDR 623.681.388	IDR 623.681.388	IDR 623.681.388	IDR 623.681.388
Cash difference	IDR 621.000.000	-IDR 12.195.276	-IDR 2.001.053	IDR 8.415.114	IDR 19.059.006	IDR 29.936.570
Initial cash difference		-IDR 621.000.000	-IDR 633.195.276	-IDR 635.196.329	-IDR 626.781.215	-IDR 607.722.209
Balance	-IDR 621.000.000	-IDR 633.195.276	-IDR 635.196.329	-IDR 626.781.215	-IDR 607.722.209	-IDR 577.785.639

Source : Author Analysis, 2025.

Based on table 4 above. which is the result of cash flow analysis during the five-year period. it is obtained that the total income generated from operational activities has not been able to cover the initial investment costs and annual operational expenses. The annual cash difference shows a consistently negative value. indicating that the cash inflow is smaller than the cash outflow. This causes the cumulative cash balance to continue to decline. with the final balance in the fifth year recorded at -IDR 577.785.639. Thus. it can be concluded that the investment does not generate sufficient cash flow to return the initial capital within the planned period. and overall indicates an unhealthy cash flow condition from a financial feasibility perspective.

4.3 NPV Analysis

The following is a table of the processed NPV analysis:

Table 5. Net Present Value

Discount Rate = 5%	Year					
	0	1	2	3	4	5
Income						
Operational Income		IDR 611.486.112	IDR 621.680.335	IDR 632.096.502	IDR 642.740.394	IDR 653.617.958
Depreciation						IDR 310.500.000
Total Income		**IDR 611.486.112**	**IDR 621.680.335**	**IDR 632.096.502**	**IDR 642.740.394**	**IDR 964.117.958**
Outcome						
Investment cost	IDR 621.000.000					
Fixed cost		IDR 215.635.308	IDR 215.635.308	IDR 215.635.308	IDR 215.635.308	IDR 215.635.308
Variable cost		IDR 188.086.080	IDR 188.086.080	IDR 188.086.080	IDR 188.086.080	IDR 188.086.080
Other cost		IDR 219.960.000	IDR 219.960.000	IDR 219.960.000	IDR 219.960.000	IDR 219.960.000
Total Outcome		**IDR 623.681.388**	**IDR 623.681.388**	**IDR 623.681.388**	**IDR 623.681.388**	**IDR 623.681.388**
Profit/Loss	-IDR 621.000.000	-IDR 12.195.276	-IDR 2.001.053	IDR 8.415.114	IDR 19.059.006	IDR 340.436.570
NPV			**-IDR 344.739.419**			
IRR			**-11%**			
PBP			**276260581,3**			

Source : Author Analysis, 2025.

Based on the results of the net present value (NPV) calculation in table 6 above, the results obtained were negative, namely - IDR 344.739.419 so it can be said that the investment used for an investment period of 5 years is **not feasible** to do.

4.4 Internal Rate of Return (IRR) Analysis

Based on the IRR calculation results in table 5 above. The calculated IRR value is -11%. which is significantly lower than the interest rate used. This indicates that the rate of return on the investment is below the cost of capital that must be borne. Thus, it can be concluded that this investment is not financially feasible.

4.5 Payback Period (PBP) Analysis

Based on the results of the Payback Period (PBP) analysis and the calculation of Vehicle Operating Costs (VOC) per year, it is known that the company has not been able to reach the break-even point within a period of five years. This indicates that the cash flow generated during the period is not sufficient to cover the initial investment.

4.6 Vehicle Rental Analysis

The following is the price for renting a vehicle to PT Dapensi Dwi Karya (DDK)

Table. 6 Vehicle Rental Prices

No.	Vehicle type	Capacity	Rental price / month	Rental price / day
1	Colt Diesel Engkel (CDE)	4-5 tons	IDR 28.300.000	IDR 1.088.462
2	Colt Diesel Double (CDD)	8 tons	IDR 38.700.000	IDR 1.488.462
3	Fuso	10-12 tons	IDR 48.500.000	IDR 1.865.385

Source : PT Dapensi Dwi Karya, 2024.

4.7 Sensitivity Analysis

Sensitivity analysis is essential, as it provides deeper insight into how fluctuations in key cost components affect the overall financial outcome. It enables the authors to identify which variables have the most significant impact (Jasmine et al., 2025), especially on the Net Present Value (NPV), thereby highlighting the cost factors that are most critical to the investment's financial feasibility. Table 7 presents the results of the sensitivity analysis, showing how variations in several cost components affect the calculation of NPV.

Table. 7 Sensitivity Analysis

Factors	-20%	-10%	0	10%	20%
Fuel cost	-IDR 221.816.917	-IDR 283.278.168	-IDR 344.739.419	-IDR 406.200.670	-IDR 467.661.920
Salary	-IDR 269.554.524	-IDR 307.146.971	-IDR 344.739.419	-IDR 382.331.866	-IDR 419.924.314
Rent cost (FUSO)	IDR 717.384.972	IDR 465.409.378	IDR 213.433.784	-IDR 38.541.810	-IDR 290.517.404
Rent cost (CDD)	IDR 1.124.702.054	IDR 923.641.095	IDR 722.580.137	IDR 521.519.178	IDR 320.458.219

Source : Author Analysis, 2025.

Table 7 demonstrates that price fluctuations significantly affect NPV outcomes. An increase in fuel costs by 10% and 20% leads to a lower NPV of –IDR 406,200,670 and –IDR 467,661,920, respectively. Similarly, an increase in driver salaries also causes the NPV to decline. The sensitivity analysis of FUSO rental costs shows that a 10% or 20% increase also results in negative NPV values. However, due to the actual volume of goods being consistently below the maximum vehicle capacity, the use of FUSO trucks, whether owned or leased, is considered inefficient. In contrast, leasing a CDD-type truck appears to be a more efficient and financially viable option. Even even in scenarios where the rental cost increases or decreases, CDD rental produce a positive NPV.

DISCUSSION

As shown in section 4.1.5 and Table 3, the owned FUSO vehicle has a daily VOC of IDR 1.998.978, slightly higher than the rental cost of IDR 1,865,385. Although the difference appears minor, financial feasibility analysis reveals that vehicle ownership requires an initial investment of IDR 621.000.000, with projected annual revenues ranging from IDR 611.486.112 to IDR IDR 653.617.958 over five years. A residual value of IDR 310.500.000, equivalent to approximately 50% of the vehicle's purchase price (based on used vehicle market estimates), is included in the final year. However, due to consistently high annual operating costs (around IDR 622.884.960), the resulting cash flows are insufficient to recover the investment. The calculated NPV is –IDR 344.739.419, indicating financial infeasibility. This is further supported by a negative IRR and a Payback Period that exceeds five years, confirming that the investment fails to reach break-even within the project timeframe.

In addition to the financial analysis, field observations reveal that the current utilization of the FUSO truck is notably low, with a considerable portion of its cargo space left unused during daily operations. On average, the vehicle carries only around 4-6 tons of goods per day, despite having a capacity of 8 to 12 tons—resulting in a utilization rate of less than 50%. This inefficiency indicates a mismatch between vehicle capacity and actual distribution needs. In contrast, the CDD-type truck, with a maximum load capacity of 8 tons and a lower daily rental cost of IDR 1.488.462, offers a more practical and cost-efficient alternative. Its capacity is better aligned with the company’s typical shipment volume. Furthermore, sensitivity analysis confirms the robustness of this option. The CDD truck consistently produces positive NPV values, demonstrating strong financial feasibility across different cost conditions. Therefore, it is recommended that the company transition from FUSO trucks to leasing CDD units to enhance operational efficiency and optimize cost-effectiveness in fleet management.

The findings of this study indicate that vehicle leasing is a more feasible option compared to owning, particularly in distribution routes characterized by low cargo volume and suboptimal vehicle utilization. This contrasts with the study by Yanuar & Utama (2015), which concluded that for long-distance routes such as Bandung–Surabaya, investing in privately owned vehicles is more beneficial due to higher volume and usage intensity. On the other hand, the results of this research align with the study by de Sá (2022), which suggests that although vehicle ownership may offer lower operating costs, outsourcing or leasing provides advantages in service quality and operational flexibility—factors that are crucial for improving distribution efficiency. Furthermore, this study supports the findings of Dasgupta et al. (2007), who argue that leasing is more suitable in situations where vehicles incur high maintenance costs and have low utilization rates. In this study's context, this is evident in the underutilization of FUSO trucks. A more recent study by Tuomela (2024) also reinforces the argument that leasing enhances operational flexibility and is often considered strategically advantageous, particularly in dynamic market conditions. Therefore, the decision to lease or purchase logistics vehicles should not rely solely on financial aspects but must also consider strategic factors such as flexibility, fleet utilization efficiency, and operational resilience amid demand fluctuations.

The results of this study carry important practical and strategic implications for logistics companies in making fleet selection decisions. From a practical perspective, leasing vehicles offers better cost efficiency, especially in situations where cargo volumes do not fully utilize the capacity of owned vehicles—as observed in the use of FUSO trucks on the Bandung–KTSH route. Leasing also reduces the burden of upfront capital investment, maintenance costs, and the risk of asset depreciation. Strategically, outsourcing enhances operational flexibility, allowing companies to respond more quickly to demand fluctuations, route changes, or temporary service requirements.

Although this study includes sensitivity analysis of selected cost parameters, the analysis is limited to one variable from fixed costs (salaries) and one from variable costs (fuel). In addition, this study does not include an assessment of operational risk or other non-financial dimensions such as service quality and vendor reliability for vehicle rentals. These limitations suggest that future research should adopt a more holistic approach by incorporating multi-parameter sensitivity analysis, as well as risk evaluation, to provide a broader understanding of the financial and strategic implications of fleet selection and logistical decision-making.

5. CONCLUSION

Based on the financial analysis, field observations, and sensitivity testing, this study concludes that leasing CDD-type trucks is a more financially and operationally viable option compared to owning FUSO vehicles for the Bandung–KTSH distribution route. The consistently low utilization of FUSO trucks, combined with high operational costs and negative investment indicators such as NPV, IRR, and Payback Period, demonstrates that vehicle ownership is not feasible under current conditions. In contrast, CDD trucks offer better alignment with actual cargo volume, lower daily rental costs, and strong financial performance across various cost scenarios. These findings underscore the importance of matching vehicle capacity to operational needs and highlight the strategic advantages of outsourcing in enhancing flexibility and cost efficiency. Therefore, leasing appropriately sized vehicles, such as CDD units, is recommended as a more sustainable and adaptable solution for logistics operations with fluctuating or moderate demand.

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Analysis of Variation in the Number of Layers in the Hardfacing Process of ASTM A216 WCB Material on Hardness, Wear, and Microstructure

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Buffer layer ; Hardfacing ; Hardness ; Wear Resistance; Microstructure

Abstract

ASTM A216 WCB material is a cast carbon steel commonly used in valve components operating at high temperatures, where one of the main problems is surface wear. This study aims to analyze the effect of variations in the number of Stellite 12 hardfacing layers and the type of buffer layer (ER308 and ER309) on the hardness, wear resistance, and microstructure of ASTM A216 WCB material. Four variations of specimens were tested using the Gas Tungsten Arc Welding (GTAW) welding process. The hardness test results showed that increasing the number of layers consistently increased the material hardness due to reduced dilution and microstructural refinement. The highest hardness value of 477.89 HV was recorded in the specimen with the ER309 buffer layer and four layers of hardfacing. In contrast, the lowest wear rate, which indicates the highest wear resistance, was 0.00318 mm^3/Nm and was observed in the specimen with the ER308 buffer layer and two layers of hardfacing, which had a lower surface hardness (396.13 HV). These results indicate a non-linear relationship between maximum hardness and optimal wear performance. Microstructural observations indicate that the base metal has a ferrite and pearlite structure. In the buffer layer, austenite and vermicular ferrite structures are formed. Meanwhile, in the hardfacing layer, α-dendritic phases and complex carbide precipitation were found, which were presumptively identified as M23C6. This study concludes that optimizing hardfacing performance on WCB steel requires a balance between the hardness achieved through the number of layers and the microstructural toughness influenced by the interaction with the buffer layer.

1. INTRODUCTION

The rapid development of the industrial sector has led to an increase in the use of pipes as a means of transporting water, oil, gas, and various other types of fluids. In a piping system, there is an element known as a valve. A valve is a mechanical component specifically designed to control, regulate, and guide the speed of fluid flow by opening, closing, or partially opening the flow pressure rate (Maulana et al., 2020). In addition to opening or closing the flow, the valve also functions to regulate flow speed, direct flow, prevent backflow, control pressure, or reduce pressure (Yusim et al., 2020). Valves have an important part, one of which is the disc component. The valve disc is a component that functions to control the flow of fluid through the valve. The disc is the part that experiences direct friction with the fluid, so increasing its hardness is very important, as it can improve resistance to damage caused by friction. The carbon steel material that is usually used is the ASTM A216 WCB type. This material is widely used in the valve body manufacturing process because of its balance of mechanical properties, toughness, and ease of fabrication process up to temperatures of 425°C (JC Casting, 2025).

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ASTM A216 WCB material is resistant to wear, but when used in the field, wear will decrease, causing a short service life and high maintenance costs. Therefore, it is necessary to coat the surface of the material to improve the performance and durability of the material using hardfacing. Hardfacing is used on parts that experience extreme wear, impact, and corrosion (Tandon et al., 2023). This method can also increase surface resistance in low-carbon steel (Chotěborský et al., 2008) in (Susetyo et al., 2021). Hardfacing overlay is a process of hardening a metal surface by adding a filler metal that has high wear resistance and hardness to the base metal surface (Jong et al., 2021). Hardfacing can be applied to new components during their manufacture or to restore worn surfaces (Garbade et al., 2021). Among various hardfacing alloys, cobalt-based alloys such as Stellite are known to have superior wear resistance, corrosion resistance, and high-temperature hardness retention, mainly due to their microstructure consisting of a cobalt-chromium (Co-Cr) matrix strengthened by hard carbide precipitation (Gonçalves Júnior et al., 2024).

Welding is an inseparable part of industrial development because of its role in the engineering process and product repair of metal materials (Herizal et al., 2020). Gas Tungsten Arc Welding (GTAW) is carried out by heating the metal until it melts using an electric arc formed from tungsten and a metal electrode. The electrode functions as a support for the creation of an electric arc; this classifies GTAW electrodes as non-consumable electrodes. (Abdullah et al., 2021). Gas Tungsten Arc Welding (GTAW) is a welding process that has good visual quality and is a precision welding process (Badheka et al., 2016). Welding parameters such as welding current, arc voltage, welding speed, torch angle, welding wire length, nozzle distance, welding position and direction, and welding flow rate (Karadeniz et al., 2007) in (Azwinur et al., 2020). Heat input in welding greatly affects the phase structure, cooling rate, and distortion (Fauzi et al., 2024). Optimal buffer layer selection is an important technique to reduce the propagation of defects from the substrate to the coating and prevent the occurrence of defects due to stress after the welding process (Rana et al., 2023).

According to the Schaeffler diagram, which predicts the microstructural phases in stainless steel welds based on chromium and nickel equivalents, ER309 has a higher alloy content than ER308 (Australian Stainless Steel Development Association, 2012). Darmo and Prihadianto performed hardfacing with AWS A5.13 electrodes (JIS Z 3251) on steel with varying manganese content of 10.4, 11.6, 12.7, 13.6, and 14.6 wt.%, resulting in hardness between 230 and 250 HV (Darmo et al., 2023). Susetyo et al. performed a hardfacing process using three layers of AWS A5.13 EFe2 electrodes interspersed with E7018 electrodes as buffer layers and current variations of 90, 110, and 130 A, resulting in the highest hardness in samples welded with a current of 130 A (Susetyo et al., 2021). The high alloy content of ER309 provides resistance to Fe dilution from carbon steel, thereby preventing the formation of a brittle martensite phase and producing a more ductile joint. In contrast, the performance of ER308, which has a lower alloy content, is more sensitive to process parameters and the level of dilution. In addition to buffer layer selection, the number of hardfacing layers is also a critical parameter for controlling dilution. Multi-layer deposition ensures the surface layer has the purest chemical composition for optimal wear resistance. Furthermore, the repeated thermal cycles of this process serve as an in-situ heat treatment that refines the dendritic structure, distributes carbides homogeneously, and ultimately increases hardness (Luijan et al., 2023).

Although the principle of hardfacing is well understood, systematic comparative studies on the interactive effects between the type of buffer layer (ER308 vs. ER309) and the number of Stellite 12 hardfacing layers on ASTM A216 WCB substrates are still very limited, as existing studies tend to focus on a single variable. Therefore, the research gap in this study is the lack of understanding of how the specific combination of these two factors simultaneously affects the evolution of the resulting hardness, wear, and microstructure values. The novelty of this study lies in the systematic investigation of these interactions, with the aim of identifying the relationships between process parameters, structure, and properties, and revealing the potential for an optimal balance between maximum hardness and highest wear resistance for industrial applications.

2. METHOD

The basic material used in this study is ASTM A216 WCB cast carbon steel with dimensions of 150 mm × 150 mm × 10 mm. The filler metals used are ER308 and ER309 as buffer layer s and Stellite 12 as hardfacing layer material. The chemical composition of ASTM A216 WCB material is presented in Table 1. This study uses a factorial design that produces four variations of specimens by varying the type of buffer layer (ER308 and ER309) and the number of hardfacing layers (two and four layers). The welding process used is Gas Tungsten Arc Welding (GTAW) with a downhand welding position (1G). The welding parameters used for each specimen are detailed in Table 2.

Table 1. Chemical Composition of ASTM A216 WCB

Grade	**C**	**M N**	**Si**	**S**	**P**	**CR**	**This**	**Mo**	**Cu**	**V**
ASTM A216 WCB	0.3	1	0.6	0.035	0.035	0.5	0.5	0.2	0.3	0.003

Table 2. Welding Parameters

Marking	**Electrode**	***Ampere*** **(A)**	***Voltage*** **(V)**	***Layer of Weld***	***Travel Speed*** **(mm/min)**	***Heat Input*** **(KJ/mm)**
Specimen 1	ER308	135	13	*Layer* 1	61.73	1.81764
				Layer 2	64.38	1.95696
	Stellite 12	145	14	*Layer* 3	64.38	1.95692
				Layer 4	63.56	1.91632
Specimen 2	ER308	135	12	*Layer* 1	59.29	1.98936
				Layer 2	59.06	1,79388
	Stellite 12	145	13	*Layer* 3	64.38	1.78698
			14	*Layer* 4	64.66	1.95692
				Layer 5	63.03	1.98940
				Layer 6	62.73	1.96504
Specimen 3	ER309	135	12	*Layer* 1	60.24	1.63944
				Layer 2	63.03	1,62000
	Stellite 12	145	14	*Layer* 3	63.03	2.02188
				Layer 4	62.76	1.96504
Specimen 4	ER309	135	12	*Layer* 1	61.98	1.69884
				Layer 2	61.73	1,70586
	Stellite 12	145	13	*Layer* 3	64.10	1.94068
			14	*Layer* 4	63.56	1.96504
				Layer 5	63.83	2,00564
				Layer 6	64.38	1.94880

After the welding process, a series of tests were conducted for characterization. Vickers hardness testing was performed using a load of 10 kgf with a holding time of 12 seconds. Indentations were performed on the base metal, HAZ, both buffer layers, and each hardfacing layer. This study was exploratory in nature to identify metallurgical trends and phenomena. Each condition variation was represented by one specimen (n=1). Therefore, inferential statistical analysis such as two-factor ANOVA cannot be applied to claim statistical significance. Claims in this manuscript are based on the analysis of trends observed from the data and supported by metallurgical principles. Hardness testing was performed with three indentations per location to provide a measure of local variability. Wear performance was evaluated using the pin-on-disc method in accordance with ASTM G99-17, Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. The pin-shaped test specimens were cut from the layer of hardfacing on top of every variation. Testing is done by pressing the pin on the disc coated with rotating abrasive SiC paper with 60 grit. The test parameters used are a normal load

of 1086 g (10.65 N), a trail radius of 100.58 mm, a spin speed of 1326.2 RPM, and a duration of 1 minute. For microstructure analysis, the specimen was cut transversely, polished, and etched in a chemical way. Two types of reagent etching were used: Nital solution (3% HNO_3 in ethanol) for the base metal and HAZ areas, as well as Aqua Regia solution (1 part HNO_3 and 3 parts HCl) for the buffer layer and hardfacing layer areas. Observation of the microstructure is done using microscope optics

3. RESULT AND DISCUSSION

3.1 Hardness Testing

Hardness testing was carried out to determine the hardness value of each specimen from various variations in this study, including the base metal, HAZ, buffer layer, and each layer of the hardfacing layer.

Table 3. Hardness Test Results

Variation	Location	Hardness Test Value (HV)			Average (HV)
		To 1	2nd	The 3rd	
Specimen 1 (Buffer layer ER308, 2 Layer Hardfacing)	Base metal	157.13	163.35	155.95	158.81
	HAZ	164.61	171.55	231.98	189.38
	Buffer layer 1	261.35	274.05	265.93	267.11
	Buffer layer 2	329.24	279.5	261.91	290.22
	Hardfacing Layer 1	315.66	361.07	352.00	342.91
	Hardfacing Layer 2	379.94	412.90	395.54	396.13
Specimen 2 (Buffer layer ER308, 4 Layer Hardfacing)	Base metal	160.48	157.86	160.38	159.57
	HAZ	167.50	155.54	160.33	161.12
	Buffer layer 1	307.49	319.08	317.49	314.69
	Buffer layer 2	361.71	389.23	386.39	379.11
	Hardfacing Layer 1	403.52	440.31	423.83	422.55
	Hardfacing Layer 2	411.74	444.85	470.77	442.45
	Hardfacing Layer 3	443.33	502.14	502.41	482.63
	Hardfacing Layer 4	442.68	489.25	455.04	465.32
Specimen 3 (Buffer layer ER309, 2 Layer Hardfacing)	Base metal	157.77	162.86	158.78	159.81
	HAZ	174.24	170.87	168.25	171.12
	Buffer layer 1	181.85	212.11	206.14	200.03
	Buffer layer 2	373.66	206.55	210.96	263.72
	Hardfacing Layer 1	436.47	408.46	418.02	420.98

Variation	Location	Hardness Test Value (HV)			Average (HV)
		To 1	2nd	The 3rd	
	Hardfacing Layer 2	474.11	462.34	437.74	458.06
Specimen 4 (Buffer layer ER309, 4 Layer Hardfacing)	Base metal	153.22	167.8	159.3	160.11
	HAZ	168.86	173.65	167.60	170.04
	Buffer layer 1	262.63	283.34	232.72	259.36
	Buffer layer 2	267.63	408.65	248.4	308.23
	Hardfacing Layer 1	343.71	351.24	352.77	349.24
	Hardfacing Layer 2	345.65	483.10	490.34	439.70
	Hardfacing Layer 3	459.59	486.41	465.36	464.45
	Hardfacing Layer 4	495.67	469.35	468.64	477.89

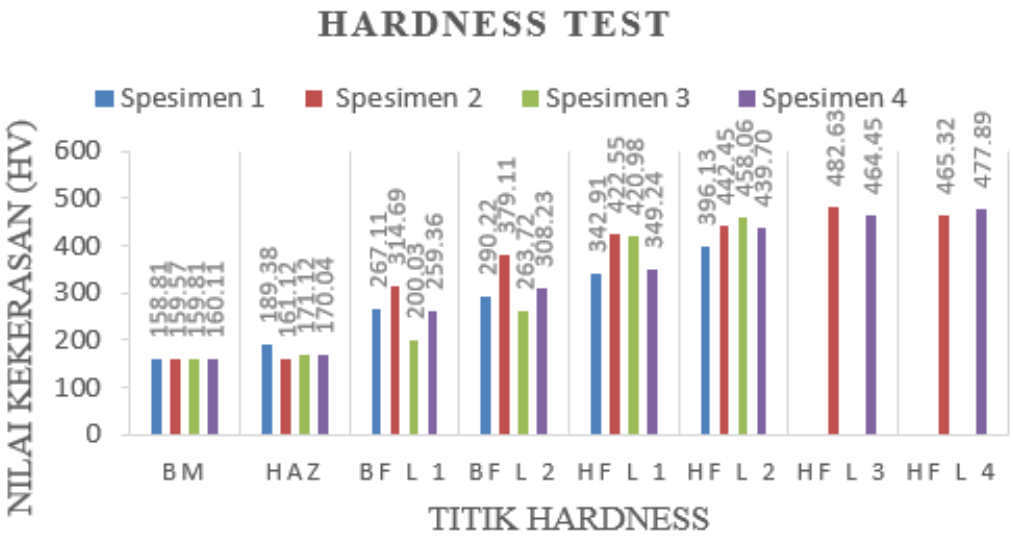

Figure 1: Hardness Test Results Graph

The average hardness of the ASTM A216 WCB base metal was consistent across the four specimens, ranging from 158.81 HV to 160.11 HV, consistent with the characteristics of cast carbon steel in its initial state. In the HAZ, a slight increase in hardness was observed, caused by the thermal cycle of welding that produces grain refinement, thus increasing the resistance to dislocation movement. The buffer layer showed a significant increase in hardness. There was a clear difference in performance between the ER308 (Specimens 1 and 2) and ER309 (Specimens 3 and 4) buffer layers. The specimens using ER308 consistently produced harder buffer layers. This difference is most likely due to the chemical composition. ER309 has higher Cr and Ni contents, which stabilize the softer and more ductile austenite phase and are more resistant to carbon dilution from the base metal. In contrast, ER308 with a lower alloy content may experience greater carbon pickup from the base metal, which may induce precipitation hardening or partial phase transformation. The Stellite 12 hardfacing layer exhibited the highest hardness increase, which is attributed to its microstructure consisting of a cobalt matrix reinforced by the precipitation of very hard complex carbides (Senthilkumar et al., 2023).

Data analysis revealed two main trends. First, increasing the number of layers from two to four consistently increased the hardness of the surface layer. The highest hardness value in the two-layer specimen (Specimen 3) was 458.06 HV, while in the four-layer specimen (Specimen 4) it reached 477.89 HV. Consequently, the top layer has a chemical composition closest to that of pure Stellite 12, allowing for the formation of a higher carbide volume fraction. Second, the hardness gradually increased with each additional layer (HF L1 to HF L4) in Specimens 2 and 4. For example, in Specimen 2, the hardness increased from 422.55 HV (HF L1) to 465.32 HV (HF L4). This phenomenon is due to the repeated thermal cycles of subsequent layer deposition acting as an in-situ heat treatment of the underlying layer, promoting grain refinement and homogenization of the structure. This confirms that to achieve optimal surface properties of Stellite alloys, multi-layer deposition is necessary to overcome the dilution effect. Overall, the measured hardness profiles provide strong evidence that the combination of buffer layer type and number of hardfacing layers interactively determines the hardness distribution across the weld deposit. The highest hardness value achieved by Specimen 4 (ER309, 4 layers) indicates that the use of a metallurgically stable buffer layer combined with a sufficient number of layers is an effective strategy for maximizing surface hardness.

3.2 Wear Testing

The wear performance was evaluated based on the specific wear rate (mm³/Nm), where lower values indicate higher wear resistance. The test results showed that all hardfacing configurations drastically improved the wear resistance compared to the ASTM A216 WCB base material. The wear rate of the base material was 0.01338 mm³/Nm, while all coated specimens had wear rates below 0.006 mm³/Nm. The most prominent finding is the existence of a non-linear relationship between surface hardness and wear resistance, which is often referred to as the hardness-wear paradox.

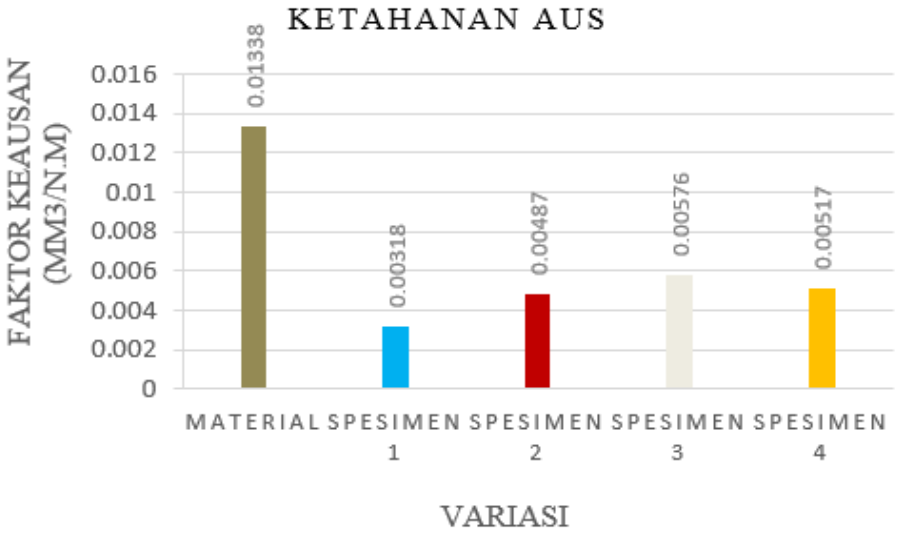

Figure 2: Wear Test Results

This phenomenon can be explained by the complex microstructural mechanisms in cobalt-based alloys. The wear resistance of Stellite alloys is determined not only by the volume fraction of hard carbides but also by the ability of the more ductile α-Co matrix to support these carbides and resist plastic deformation under shear stress from abrasive particles (Crook, 2022). In Specimen 4, the very high hardness is most likely due to the very high carbide density, which can cause matrix embrittlement. Under abrasive loading, this brittle matrix may not be able to effectively support the carbide particles, leading to the release of hard particles (carbide pull-out). These released particles then act as a third-party abrasive particle (third-body abrasive), which precisely speeds up the wear rate. In contrast, Specimen 1, although softer, possibly has its own optimal balance between hardness and toughness. Its matrix is more tenacious, capable of supporting the phase carbide in an effective way, absorbing part of the energy from the abrasion process, and preventing premature particle release. With that said, although its own violence is absolutely lower, microstructure Specimen 1 gives superior tribology performance in this test condition. It is necessary to note that without analysis of surface wear using

Scanning Electron Microscopy (SEM), the mechanism This proposed wear is of an inferential nature and requires more validation to carry on.

3.3 Microstructure Testing

3.3.1 *Base Metal*

The microstructure of the ASTM A216 WCB *base metal can be seen in Figure 3.*

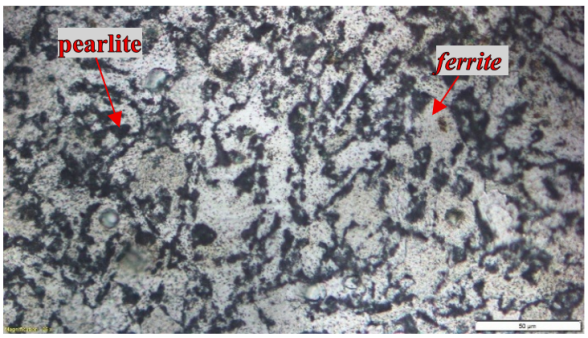

Figure: 3 *Microstructure of Base Metal*

Microstructural observations of the ASTM A216 WCB *base metal* show a typical medium carbon steel structure, consisting of ferrite (bright areas) and pearlite (dark, lamellar areas). This structure is consistent with the initial state of the material and does not show significant changes, indicating that this zone has not experienced high enough thermal cycling to trigger phase transformation.

3.3.2 Buffer layer

The microstructure of the buffer layer looks like Figure 4.

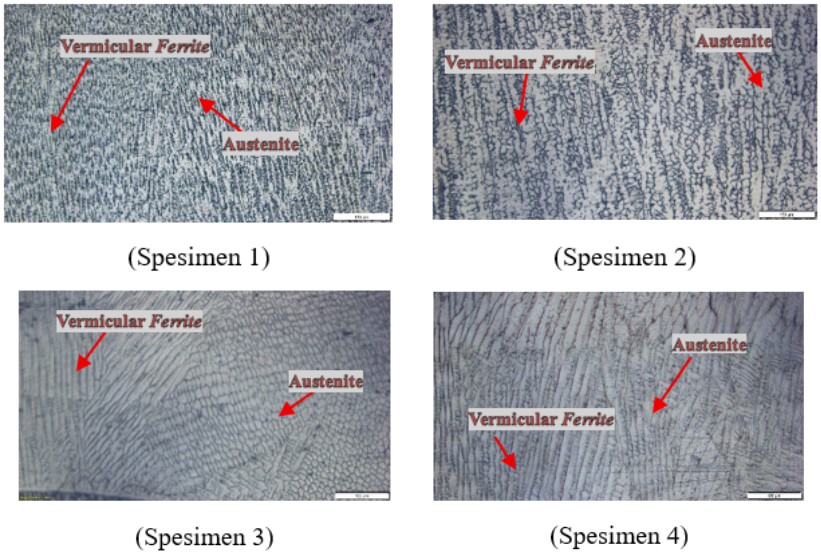

Figure 4: Microstructure Buffer layer

The microstructure of both types of buffer layers is dominated by a light austenite matrix with a vermicular ferrite phase (worm-shaped, dark) dispersed within it 4. The formation of this ferrite is important to prevent hot cracking during solidification. There are differences in morphology between specimens using ER308 and ER309. Specimens with the ER309 buffer layer (Specimens 3 and 4) tend to show a finer structure. This is due to the higher Cr and Ni contents in ER309, which produce a more stable austenite matrix and promote the formation of finer and more evenly distributed ferrite. This higher austenite stability provides better resistance to dilution and thermal stress, which are the main functions of the buffer layer (Kalyankar et al., 2020). An even distribution of ferrite tends to increase toughness while maintaining corrosion resistance (Hassel et al., 2025). Specimen 2 shows a more dominant and longer ferrite structure in the crystal orientation direction. This

increase in ferrite volume indicates a faster cooling rate or local composition differences due to variations in the welding process. Although ferrite can increase strength and heat resistance, excess ferrite can reduce corrosion resistance if it exceeds the optimum limit (Hassel et al., 2025). Specimen 3 shows a finer structure than 1 and 2. Ferrite is in the form of small and short ribbons, scattered among the austenite phase, which appears more dominant. This indicates that ER309, which has a higher Cr and Ni content, produces a more stable structure with austenite phase dominance. Meanwhile, in specimen 4, the ferrite structure appears to be more elongated, but not as much as in specimen 2. This structure indicates that although austenite is still dominant, there is an influence of the cooling rate and the addition of Cr elements in ER309, which triggers the formation of vermicular ferrite in larger quantities than in specimen 3.

3.3.3 Hardfacing Layer

The microstructure of the hardfacing layer is shown in Figure 5.

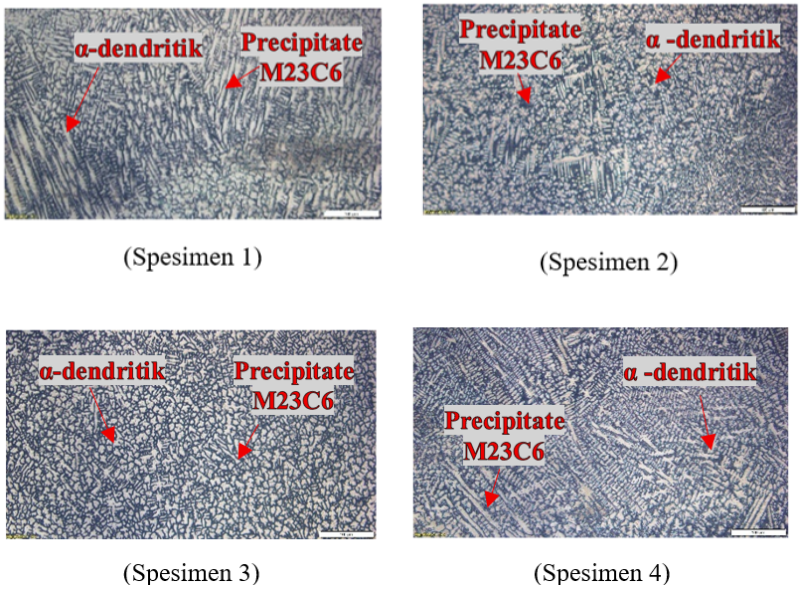

Figure 5: Microstructure of Hardfacing Layer

The microstructure of the Stellite 12 hardfacing layer (Figure 5) shows a classic hypoeutectic structure consisting of a dendritic cobalt-rich matrix (α-Co phase) with a eutectic network of hard precipitates in the interdendritic regions. Based on the known morphology and chemical composition of the Stellite 12 alloy, these precipitates are presumptively identified as complex carbides, most likely of the M23C6 and/or M7C3 type, where 'M' represents carbide-forming elements such as Cr, W, and Co. Definitive identification of these carbide phases requires advanced characterization techniques such as X-ray Diffraction (XRD) or Energy-Dispersive X-ray Spectroscopy (EDS) analysis in SEM, which is a limitation of this study but an important direction for future investigations. The number of hardfacing layers shows a clear influence on the microstructural fineness. The four-layer specimens (specimens 2 and 4) exhibit a finer dendritic structure and more evenly distributed carbide precipitates in the top layer than the two-layer specimens (specimens 1 and 3). This phenomenon occurs because the repeated thermal cycles of subsequent layer deposition act as in-situ heat treatments on the underlying layers, promoting grain refinement and structural homogenization. The finer and more homogeneous microstructure of Specimen 4 correlates well with its highest hardness value. Conversely, the slightly coarser structure of Specimen 1 likely provides higher matrix toughness, contributing to its superior wear performance.

4. CONCLUSION

This study systematically analyzes the effect of variations in buffer layer s (ER308 and ER309) and the number of Stellite 12 hardfacing layers (two and four layers) on ASTM A216 WCB material. Based on the results and discussion, several conclusions can be drawn, namely, increasing the number of hardfacing layers from two to four layers consistently increases the surface hardness. The highest hardness (477.89 HV) was achieved by specimens with ER309 buffer layer s and four layers of hardfacing. This increase is due to the reduced dilution effect of Fe from the substrate and the refinement of the microstructure due to repeated thermal cycles. A non-linear relationship between hardness and wear resistance was found. The highest abrasive wear resistance performance, characterized by the lowest wear rate (0.00318 $mm^3/N \cdot m$), was achieved by the specimen with an ER308 buffer layer and two layers of hardfacing, despite having a lower surface hardness (396.13 HV). The main contribution from this research is the demonstration of the empirical existence of the paradox of wear-hardness in this hardfacing system. This underlines that for application wear-out abrasives, optimization performance does not always mean maximizing violence, but rather reaching a balance of optimal microstructure between phase volume fraction and hard and tough carbide matrix for his supporters

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